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Determining stiffness modulus by means of different mechanical testing

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Abstract. Many research on mechanistic testing have come to likely conclusion that different test setup results in different performance. The aim of this paper is to analyse the stiffness modulus resulting from three different test setups, namely; Monotonic Uniaxial Tension Test (MUTT), Monotonic Uniaxial Compression Test (MUCT), and Indirect Tensile Test (ITT). They are monotonic tests. This paper will elaborate if there is any significant difference among the result of the first three tests. Master curves of stiffness modulus as a function of strain rate at reference temperature of 15°C were developed. The results show that there is no significance difference between the modulus resulting from the three tests performed at high strain rates. It's also shown that at low strain rate, the elastic modulus resulting from compression tests is in between indirect and uniaxial tension test's elastic modulus.

1. Introduction

There are several type of test to determine the modulus of asphalt mixtures. Mamlouk, Walubita, Li, Pramesti and Molenaar [1-5] are among researches who conducted these kind of tests for gaining this purpose. Mamlouk, claimed in his literature review on Modulus of Asphalt mixtures, that different setups, different test conditions such as loading frequency, magnitude, and the duration of a test will produce a different value of the asphalt mixture modulus [1].

This modulus test setup basically records stress and strains of the specimens as a response of a particular strain rate at a certain load temperature. A typical stress-strain relation is then developed. From this relation both tangent and secant modulus can be determined.

Three out of many modulus tests are Uniaxial monotonic compression test, Uniaxial monotonic tension test, and Indirect tension test. For the practical purposes, Indirect tensile test is the most suitable due to its simplicity in specimen preparation and test procedure. However, the question arises whether the ITT gives results which are comparable to the results obtained by means of other tests.

Nevertheless, the three tests have similarity which is monotonic loading. It should be emphasized that this work is limited to the monotonic loading test. Researcher interested on the modulus and stress dependency on the cyclic loading should refer to Medani [6] and Li [4].

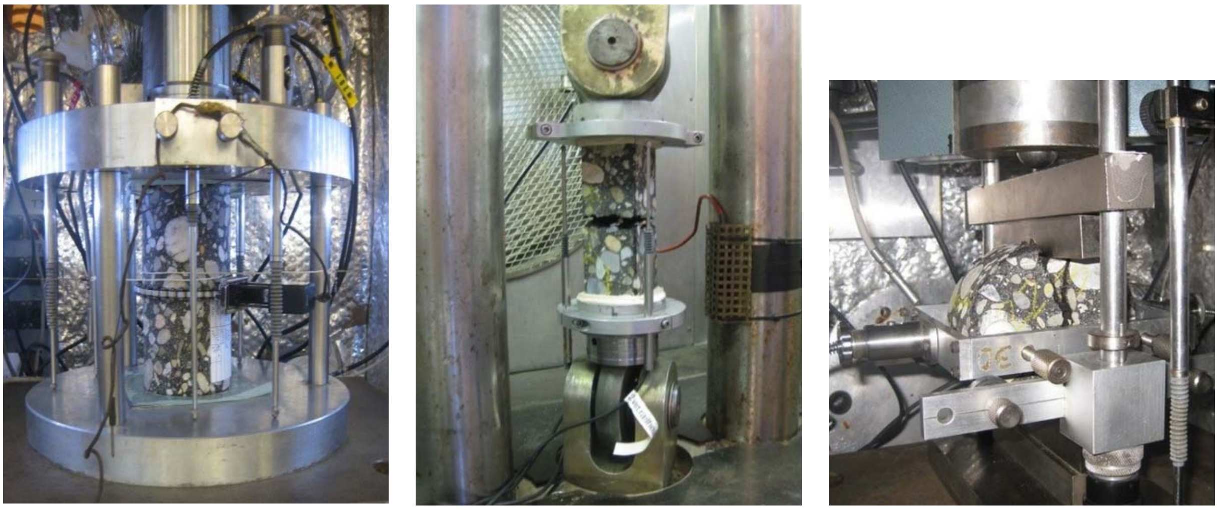
The dependency of the asphalt mixture response on time loading and temperature cannot be neglected in the determination of asphalt mixture modulus. However, in a special condition where an intended use of result and level accuracy required in the analysis, thus behavior can be approximately consider as elastic.

The objective of this paper is to analyze the stiffness modulus resulting from three different test setups, namely; Monotonic Uniaxial Tension Test, Monotonic Uniaxial Compression Test, and Indirect Tensile Strength Test. Li [4], reported that the stiffness determined using a bending test and a compression/tension test are more or less in agreement with each other. Is that also the case for these three tests? This paper will discuss is there any significant difference among the result of these three tests. Master curves of stiffness modulus and strength as a function of strain rate at reference temperature of 15°C were developed and analyzed.

2. Experimental program

The specimen tested were Gravel asphalt concrete (GAC) mixtures which commonly used in minor roads and based course in the Netherlands. The 150x150x450 mm block specimens based on this gravel asphalt concrete mix design were produced in a shear box compactor. Each block were sawed or cored into specific dimensions. For the Monotonic Uniaxial Compression test (MUCT) and the Monotonic Uniaxial Tension test (MUTT), the specimen is a cylinder with h=130 mm and ∅=65 mm. For the Indirect Tension Test (Monotonic) (ITT) the specimen is cylinder with h=40 mm and ∅=100 mm. The densities of the specimens were measured. The stiffness modulus tests were performed only for specimens with density of 2394 kg/m3 to 2357 kg/m3 (air void content of 3.75% to 5.25%). The test set-up for three testing type is shown in figure 1.

2.1. Monotonic uniaxial compression test



(a) (b) (c)

Figure 1. (a) Uniaxial compression test set-up (b) The set-up of uniaxial tension test (c) Indirect tension test set-up

The Uniaxial compression test set-up is shown in figure 1(a). To avoid shear failure, the top and the bottom of the specimen was covered with a biological plastic foil attached to a thin steel plate. This steel plate and plastic together is called a friction reduction system (FRS)[5].

The strain rate used for the MUCT (and MUTT) were determined based on the relation between stiffness and strain rate at the bottom of similar pavement layer of Lintrack section tested in 1990 [5].

This relation was determined using BISAR simulation. The strain rate chosen for each temperature is depicted in the test program shown in table 1.

Table 1. The temperature and strain rate applied for MUCT, MUTT, and ITT.

	Monotonic Uniaxial Compression Test	Monotonic Uniaxial Tension Test	Indirect Tension Test	
Temp (ºC)	Strain rate $\dot{\varepsilon}$ (%/s)	Strain rate $\dot{\varepsilon}$ (%/s)	Strain rate (%/s)	Speed (mm/s)
5	0.01	0.01	0.01	0.0278
	0.1	0.1	0.1	0.2778
	0.5	0.5	0.5	1.3889
	1	1	1	2.7778
20	0.05	0.05	0.05	0.1389
	0.1	0.1	0.1	0.2778
	1	1	1	2.7778
	2	2	2	5.5556
30	0.1	0.1	0.1	0.2778
	1	1	1	2.7778
	2	2	2	5.5556
	3	3	3	8.3333

2.2. Monotonic uniaxial tension test

The testing program of the MUTT is depicted in table 1. It can be seen that the strain rate chosen for each temperature is similar to the one for MUCT, to attain comparable result between those 3 tests. The test set-up is shown in figure 1(b).

2.3. Indirect tension test

In this test, using the same actuator and controller that were used as in the MUCT, a strip loading was applied on top of a thin disc of asphalt specimen, to determine the tensile strength of the asphalt mixture (see figure 1(c)).

The Indirect Tension Test works on deformation rate based rather than strain rate based. Similar to the MUTT, to attain a comparable result, the ITT needs to perform in similar strain rate of MUTT and MUCT. Hence, these “expected” strain rates have to translate to the deformation rate. The deformation rates in the vertical direction are determined using equation 1, which is explained briefly in other reference [5]. The deformation rate (mm/s) at y direction depicted as $\dot{U}_y$, the horizontal strain rate (1/s) depicted as $\dot{\varepsilon}_x$, and the shift factor as SF.

$$\dot{U}_y = \frac{\dot{\varepsilon}_x}{SF};\ \dot{U}_y = \frac{\dot{\varepsilon}_x}{0.0036} \quad (1)$$

Two LVDTs were installed to measure the vertical and horizontal displacements of the specimen. The results of this test are the indirect tensile strength and the deformation, and further the Poisson’s ratio as well as the stiffness of the specimen can be determined.

3. Result and discussion

3.1. Monotonic uniaxial compression test

In determining Modulus of elasticity, E, MUCT was employed. The axial strain was measured by means of LVDT attached to a platen plate while radial strain was measured by a radial chain attached to the specimen. Figure 2, shows the development of the stress at certain strain during the MUC test which was performed at different temperature and different strain rate. Hence, the tangent and secant modulus of elasticity may be determined by employing these curves.

Further, linear regression of the data points from 5% to 20% of maximum stress were used to determine the tangent modulus. This was done since the data point before 5% were unstable due to the effect of setup stretching occur in outset of the test. The solid line in the figure 3a depicts the regression. Meanwhile the secant modulus is represented by dash-line in the figure 3a. In addition, Poisson ratio was determined as the ratio of axial to radial strain at the same stress range that was used to calculate the tangent modulus (see figure 3b).

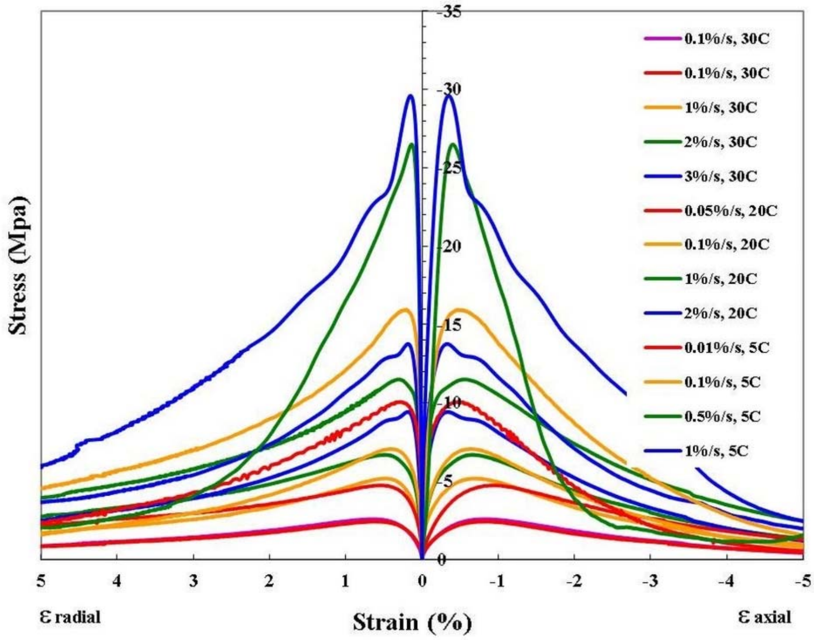


Figure 2. The development of the stress at certain axial and radial strains from MUCT at different strain rates.

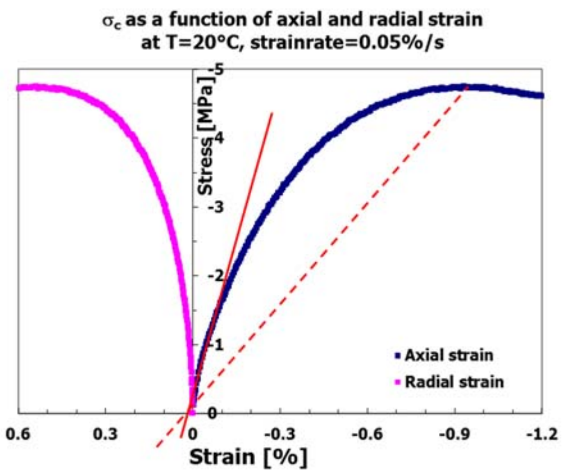


Figure 3a. E Tan (solid line) and E Sec (dashed line) of GAC tested at 20°C and 0.05%/s strain rate.

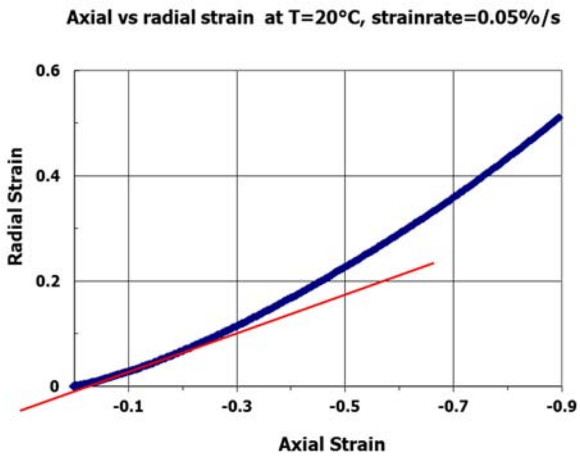


Figure 3b. Poisson's ratio (red line) as the ratio of radial strain and axial strain.

The MUCT specimen was installed between top and bottom loading platens. The friction reduction system (FRS) was affixed between specimen and the platen. The friction reduction system was made of a layer of thin sheet of steel, grease, and biological plastic on top of each other. The FRS was meant to prevent shear failure and ensure uniform uniaxial stress in all specimens' height. However, some FRS deformation in the inception of the test may influence the overall result. Therefore, correction of modulus value must be taken into account as explained by the author in other publication [5, 7]. It is imperative to note that the correction procedure only applies for the specific test setup described in this work. Other setup may employ its own procedure of correction.

The MUCT test yields data that shown in the table 2. Observation shown that dilatation may occur as the Poisson ratio increases higher than 0.5 at higher temperature. The reason for this phenomenon may be addressed to the fact that GAC mixture has big gravel stones up to 32 mm. When vertical load applied at high temperature these stones may slip laterally as the binder soften.

Table 2. Recapitulation of MUC test results.

T	Strain rate %/s	E mod MPa	Secant Modulus MPa	Poisson's ratio	f_c MPa	Total Energy J
5°C	0.01	7653	2144	0.45	-10.1	97.9
	0.1	9340	3428	0.21	-15.9	188.0
	0.5	11024	6656	0.25	-26.5	184.7
	1	27515	8439	0.37	-29.6	227.7
20°C	0.05	1028	508	0.36	-4.7	81.7
	0.1	2548	1064	0.48	-7.1	91.2
	1	10241	1989	0.52	-11.5	176.9
	2	13830	4247	0.67	-13.8	180.2
30°C	0.1	564	312	0.60	-2.4	35.7
	1	1782	741	0.63	-5.2	71.2
	2	3021	991	0.61	-6.7	100.8
	3	7700	2911	0.57	-9.4	112.4

3.2. Monotonic uniaxial tension test

The MUTT setup in this work was developed by the Road and Railway Engineering Laboratory of the Delft University of Technology and describe extensively by Erkens [8, 9]. The test exhibits '**localized failure**' in which the specimen shows cracking only in the breaking area which is mostly in the middle of the specimen. This is also confirmed by some researchers [4, 8, 9] where their MUTT specimen broke into two undamaged parts. Figure 4 presents stress-axial strain diagram from the experiment perform at temperatures of 5ºC, 20ºC and 30ºC.

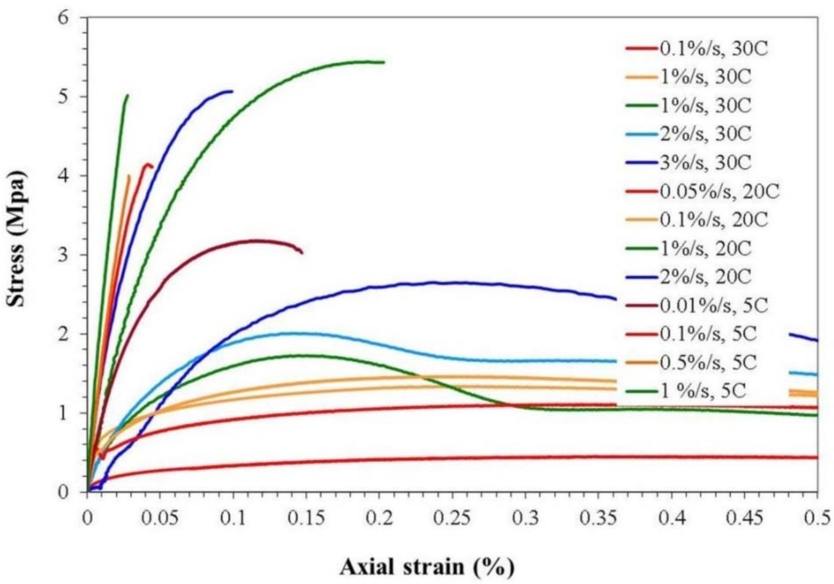


Figure 4. GAC tensile stress-strain development.

The development of tensile stress as function of axial strain is shown in the figure 4. Table 3 presents the recapitulation of the MUTT. The same approach used in sub chapter 3.1 was used to determine the tangent and secant modulus from the MUTT.

Table 3. Recapitulation of the MUT tests.

T ºC	Strain rate %/s	E mod MPa	Secant Modulus MPa	f_t MPa	Total energy J
5°C	0.01	6162	2766	3.18	1.212
	0.1	16054	9948	4.14	0.391
	0.5	19199	14030	3.99	0.200
	1	23525	18147	5.01	0.269
20°C	0.05	493	318	1.11	4.294
	0.1	1153	587	1.46	3.622
	1	8817	2842	5.44	2.769
	2	16466	5109	5.06	1.172
30°C	0.1	273	130	0.45	1.997
	1	1916	536	1.34	4.377
	1	3923	1194	1.72	3.291
	2	5002	1427	2.01	5.449
	3	3158	1136	2.59	5.521

3.3. Indirect tension test

Many researcher use the indirect tensile test (ITT) depicted in the figure 1(c) since the test is relatively easy to perform while the specimen can be easily produced. The result of the ITT is shown in figure 5 which exhibit horizontal stress versus horizontal displacement. The test also provides information about the tensile strength which can be calculated by [10]:

$$\sigma_{its} = \frac{2F}{\pi \cdot L \cdot D} \tag{2}$$

where; σ_{its} is indirect tensile strength (MPa), F is maximum vertical load at failure (N), L is height of specimen (mm), and D is the diameter of specimen (mm).

Huurman [11] developed an approach to determine the modulus of elasticity expressed in equation (3).

$$E=\frac{(1.1892 \times \nu + 0.2670)\times F}{def_{hor} \times L} \quad (3)$$

where; E is Modulus elasticity (MPa), ν is Poisson's ratio, L is the height of the specimen (mm), and F/def_{hor} is the initial slope of the force versus horizontal deformation (N/mm). The ITS results are shown in table 4.

Table 4. Recapitulation of ITS results.

T ºC	Deformation rate (mm/s)	Actual strain rate (%/s)	Air Voids %	Indirect tensile strength ($\sigma_{its}=\sigma_{xx}$) N/mm^2	Poisson 's ratio	Stiffness (Huurman) MPa
5	0.028	0.010	4.36	2.54	0.21	7201
	0.278	0.104	4.19	3.98	0.21	15699
	1.389	0.489	4.21	5.46	0.21	16097
	2.778	0.955	4.2	5.14	0.21	19479
20	0.139	0.052	4.74	1.09	0.37	4979
	0.278	0.104	4.68	1.34	0.37	5057
	2.778	1.067	4.71	2.67	0.37	10339
	5.556	2.156	4.43	3.28	0.37	11941
30	0.278	0.103	5.09	0.70	0.38	1958
	2.778	1.057	4.87	1.54	0.38	5156
	5.556	2.156	3.95	2.09	0.38	7696
	8.333	3.238	4.89	1.78	0.38	4188

The uniaxial tension test and the indirect tensile test were carried out at temperatures of 5°C, 20°C and 30°C and at strain rates ranging from 0.01 %/s to 3 %/s. Master curves of the tensile strength f_t and tensile elastic modulus E_t at reference temperatures of 15°C were developed by means of the time-temperature superposition principle. The strain rate-temperature superposition shift factor was determined by the Arrhenius equation (4).

$$\text{Log}\, \alpha_T(T) = \frac{\Delta E_a}{2.303R}\left(\frac{1}{T} - \frac{1}{T_0}\right) \quad (4)$$

$$\alpha_T=\frac{f_{shifted}}{f},\ \alpha_T=\frac{t}{t_{shifted}},\ t_{shifted}=\frac{t}{\alpha_T} \quad (5)$$

where; α_T is time-temperature superposition shift factor; ΔE_a is apparent activation energy, J/mol; R is universal gas constant, 8.314 J /(mol · K); T is temperature (K); T_0 is temperature reference (K); f is the loading frequency (Hz); $f_{shifted}$ is the shifted frequency (Hz); t is the loading time (s); and $t_{shifted}$ is shifted loading time (s).

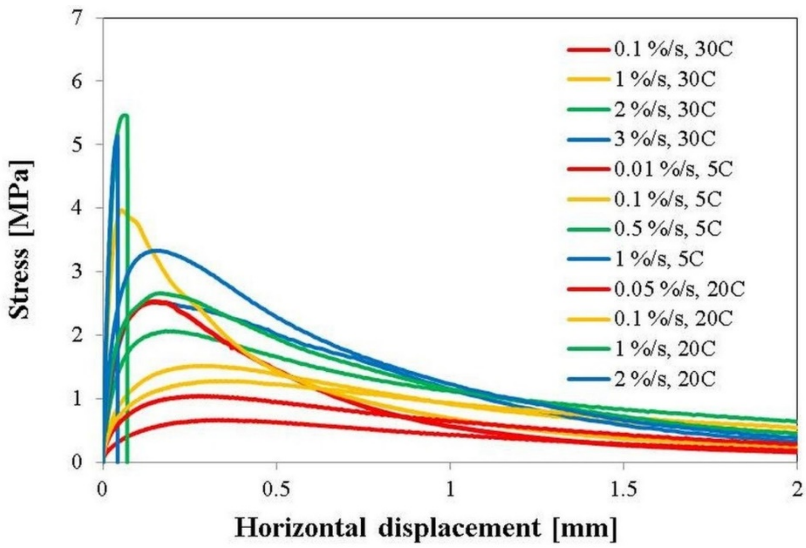


Figure 5. Horizontal stress versus horizontal displacement.

Eventually, the tensile strength ft and the tensile elastic modulus Et as a function of strain rate may be modelled by a typical Christensen-Anderson S shaped expressed in the equation (6)

$$f_t \text{ or } E_t = a_0\left[1\text{-}\exp^{\left[\frac{\dot{\varepsilon}}{a_1}\right]^{a_2}}\right] \tag{6}$$

where; a_0, a_1, a_2 are constants, $\dot{\varepsilon}$ is strain rate (%/s), f_t is tensile strength (N/mm^2), E_t is tensile elastic modulus (MPa). The tensile strength from both tests (MUTT and ITS) and the strain rates were used as input for the equation. The constants a_0, a_1 and a_2 for these two different tests were determined thanks to solver option in the Excel spreadsheet, the result is depicted in table 5.

Table 5. The constants of the GAC master curves at ref temperature of 15°C.

Master curve of		Constant		
		a_0	a_1	a_2
Tensile strength	MUTT	4.75	0.12	0.58
	ITS	5.53	0.60	0.40
Compressive strength	MUCT	34.674	3.84	0.34
Elastic modulus	MUTT	20398.81	0.60	0.87
	ITS	21332.60	1.11	0.38
	MUCT	15952.07	0.39	0.70

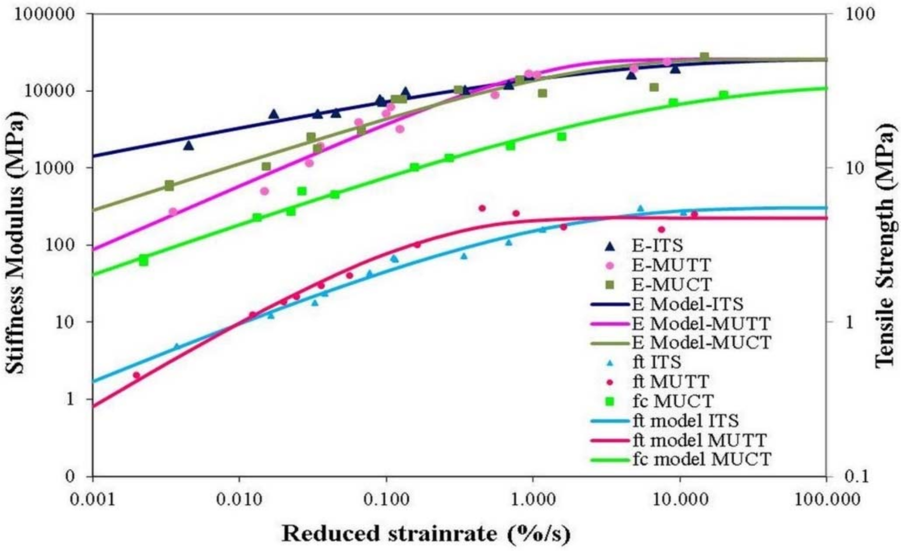


Figure 6. Master curve of Stiffness Modulus and tensile strength of Gravel Asphalt Concrete at reference temperature of 15°C.

Figure 6 depicts the master curve of the three different tests at temperature reference of 15°C. It shows that at the strain rate lower than 0.01%/s, the MUTT tensile strength is lower than the ITT tensile strength. On the other hand, in the case of strain rate from 0.01%/s to 1%/s, the ITT tensile strength is higher. Both of it coincide on top of each other after 1%/s strain rate. It is also observed that the tensile modulus of MUTT is in agreement with ITT test at the strain rate higher than 0.5%/s. The modulus elasticity calculated from MUCT (green line) is in between the modulus calculated by MUTT and ITT at low strain rate, 0.5%/s.

This implies that in cases where a uniaxial tensile test cannot be performed, realistic tensile strength estimates can be obtained by means of the indirect tensile test that is easier to employ and the specimen is simpler to manufacture.

Further, at low strain rates the compressive elastic modulus from the uniaxial test is higher than the tensile elastic modulus determined by means of the uniaxial test which is plausible because in the compression test at low strain rate -which represents high temperature due to the superposition of temperature-strain rate- the load will be carried up mainly by the aggregate skeleton rather than the bituminous mortar [5].

When comparing the MUTT, MUCT to the ITT master curve at 15°C, it will be quite obvious to note that those three graphs are in agreement to each other at high strain rates.

The temperature-strain rate relation is recapitulated in the table 6. One important finding of the master curve may be attributed to the fact that the agreement of the modulus of elasticity calculated from ITT and MUTT ceases at certain strain rate point. At a certain temperature (master curve) there is a minimum strain rate when the MUTT and ITS values more or less in agreement. At lower values than the point, however, those two curves do not fit each other anymore. These strain rates are the ceasing points. Therefore, one can make a master curve also at for example 5 degrees and 40 degrees and read at which strain rate the values (lines) are still fit to each other. Hence, the higher the temperature the higher this ceasing point, and for lower temperatures, lower strain rates are valid.

Table 6. Strain rate when the ITT and MUTT ceases in the master curve.

Reference Temperature (T_{ref}) of the master curve (°C)	Strain rate (%/s)
15	0.5
20	2

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This finding leads into the idea that ITT provide the same results as other tests but only when specific conditions are met, namely lower temperature and higher strain rate.

4. Conclusion

In this paper, the stiffness modulus has been investigated by means of three different test set up namely MUCT, MUTT, and ITT. This investigation lead into some conclusion; the tensile strength yielded from MUTT is in agreement with the Indirect Tensile Test. This is also applicable for the stiffness modulus value performed at higher strain rate. Further the agreement also applies in high strain levels which means relatively short loading times and/or low temperatures, since in the temperature higher than 15^{o}C and higher loading rate, ITT will no longer exhibit tensile stress only but demonstrates complex behaviour of tension-compression-shear. At these conditions, the ITT will no longer in agreement with MUCT and MUTT. Provided the condition above, therefore the ITT may be used to determine the tensile strength as it is more cost efficient and easier to handle than MUTT.

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