Report on new test method to determine shear properties of asphalt mixtures

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ABSTRACT

This paper is written as the shortened report of paper version published in the special issue of Road Materials and Pavement Design Journal for the purpose of presenting the results at the E&E Congress and thereby inform European audience about achieved outcomes. The focus of the paper is to present the concept of a newly developed Uniaxial Shear Tester (UST) and correlations between results from the UST and the Superpave Shear Tester (SST), a tool broadly recognized for asphalt mix design and rutting susceptibility evaluation. In this study, the UST testing principles, finite element analysis of stresses, and comparison of measured data are presented. The correlation was assessed on the basis of two tests, the repeated shear test and the small amplitude oscillation test also referred as the shear frequency sweep test. It was shown that the material characteristics determined from UST and SST are highly correlated. The dependencies are discussed in the sense of linear correlation, correlation coefficients adn coefficients of variation.

Keywords: Asphalt, Durability, Testing

FOREWORD

More detailed version of this article has been submitted to [1], the paper was selected to be published in the special RPMD journal issue [2] at the time of writing the revised version. Thus this version is written as the shortened report for the purpose of presenting the results at the E&E Congress and thereby inform European audience about achieved outcomes.

1. INTRODUCTION

One of criteria for flexible pavement design is permanent deformation. Its occurrence has a significant effect on surface water runoff and ride quality, and, most importantly, traffic safety.

Permanent flexible pavement deformations, in the form of rutting, are the combination of the irreversible deformation occurring in the subgrade, and the granular unbound material and asphalt mixture layers.

The setting of pavement design criteria for characterizing asphalt mixture premature failure in regard of resistance to permanent deformation has been studied by researchers for decades. The Marshall Stability and the Hveem Stabilometer [3] were among the forerunners of current test methodologies designed to determine specifically the asphalt mixture susceptibility to permanent deformation. These have been replaced in many countries by newer broadly recognized test methods such as the Superpave Shear Tester, the Hamburg Wheel Tracking Test, and the Repeated Load Triaxial Test.

The Hamburg-Wheel Tracking Device /HWTD/ is a test method used in both the US and Europe to assess the susceptibility of asphalt mixtures to permanent deformation. The standardized test methodology is utilized under different conditions, specimens submerged in water or cooled by air are tested at 50 or 60°C in the CEN countries /European Committee for Standardization/ and similar types of conditions are used in many US states. The Wheel Tracking Slope or Proportional Rut Depths values are further limited for various asphalt mixtures in national material specifications, although the determination of performance related rheological parameters from the HWTD is troublesome (Zak et al., 2013). For those HWTD experiments that are conducted with specimens submerged in water, it is hard to separate the effects of moisture damage and rutting resistance on total surface deformation.

McLean suggested in his work [5] that the permanent deformation of asphalt concrete (AC) layers is caused by the densification (change in the volume) and shear deformation (shape distortion) of AC under repeated traffic loads. In the case of well compacted asphalt mixtures, the densification has a comparatively small influence on the rutting. Further available information suggests that the shear deformation is the predominant rutting mechanism [6]. X-ray CT images of asphalt samples before and after heavy vehicle testing /HVS/, [7] have also showed that shear related deformation is controlling the long term rutting performance of the test sections while densification was a contributor at the very earlier stages of trafficking.

The permanent deformation response of asphalt mixtures was broadly studied as part of SHRP and reported in [8]. One of the research outcomes was the development of the Superpave Shear Tester/SST/. The test device is capable of testing both laboratory prepared specimens and cores taken from the pavement, typically with a diameter of 150 to 200 mm and height of 50 to 75 mm, with the possibility of testing prismatic specimens as well [7]. Through the application of different loading schemes, tests like the Repeated Shear Test at Constant Height, Shear Frequency Sweep at Constant Height, and Simple Shear Test at Constant Height can be performed. All tests are conducted at a constant temperature.

The validity of measured shear properties was further assessed in situ during the WesTrack project (Monismith et al., 2000) where mechanistic-empirical models were developed to represent the behavior of the pavement test sections in the accelerated pavement testing experiment using full-scale trucks. Such models are further utilized as a transfer function that relates the laboratory measured shear properties of asphalt mixtures with the in-situ asphalt mixture performance [10].

The utilization of the asphalt mixture shear properties as mix design parameters was reported in [11] and utilized in many projects since the SST device development including the reconstruction of I-710 in Long Beach (Monismith et al. 2009) and subsequent high value reconstruction projects in California. Rut depth prediction models were studied in the NCHRP 719 project [12]. In this comprehensive report, four transfer functions are assessed and differences between the Repeated Load Triaxial and Simple Shear Testing are summarized. The Repeated Shear Test at Constant Height was proved as a suitable test to predict the rutting performance of asphalt mixtures run in accordance with [13]. The rut depth transfer functions, utilizing the Repeated Shear at Constant Height Test, are implemented in CalME and MEPDG pavement design programs [12], [14].

Another test device to measure the shear properties of asphalt mixtures was developed by the GEMH-GCD Laboratory at Limognes University and France's Eurovia Research Center. [15]. The so called Double Shear Tester /DST/ is able to perform shear tests on asphalt mixture slabs with dimensions of 50x70x125mm into which four 10-mm high notches are cut near the loaded central part (60mm in width) in order to generate and localize the shear band [16]. The aim of developing the DST device was to measure the tack coat properties of asphalt mixture layers and bound in-between AC layers. The loading conditions of the DST enable the application of both monotonic and cyclic conditions [15].

The Leutner Shear Test was also developed to determine the shear properties of asphalt mixtures. This was one of the earliest works reporting the measurement of shear properties of asphalt mixtures, [17]. The idea of applying the shear load by two loading platens into one plane was further extended by the modification of the Leutner Shear Test resulting in the development of the Layer-Parallel Direct Shear Test [18], the Simple Shear Test Device [19] and the Shear Box [20]. The localization of the shear plane is given by the position of loading platens perpendicular to the core axis of symmetry. The practicability of such devices is limited and is suitable for the measurement of shear properties between two layers.

2. Uniaxial shear tester

The lack of equipment allowing the measurement of asphalt mixture shear properties in Europe and the desire to simplify the equipment compared with the SST were the motives behind this research project. Common laboratories are equipped with Universal Testing Machines /UTM/ also known as Nottingham Asphalt Testers in Europe. The Uniaxial Shear Tester (UST, see Figure 1) is an assembly that is inserted into the UTM chamber. Either a servo-hydraulic or a pneumatic press may be used to apply the shear load. The load cell measures the force values and the attached LVDT's measure the steel insert deflection.
The UST is less expensive due to the UTM's simpler construction and more applicable for many other required laboratory tests than is the single purpose SST. The SST device keeps the sample height constant with a second hydraulic piston while applying the shear load, which creates a difficult control problem.
For the UST, a hollow cylindrical specimen, as shown in Figure 2, is placed inside a steel cylinder and the load is applied through the knee joint on a steel insert placed in the center of the hollow cylindrical specimen. The dimensions of the specimen are 150mm diameter and typically height of 50mm. The steel insert is pushed down through the specimen and excites the shear load in the tested asphalt mixture. The steel cylinder restricts the asphalt mixture horizontal strain at the lateral area. Thus, the horizontal /confining/ pressure, given by the material deformation characteristics itself, occurs on the lateral sides of the specimen due to the prevented horizontal lateral deformations. The UST test assembly is axisymmetric along the vertical axis. To determine the material properties, the vertical deflection of the steel insert is measured by three LVDTs located along 120° on the steel insert. The derivation of the equation used to calculate the mechanical properties from the measured applied force and deflection can be found in [21]. The axisymmetric shear stress in the left half of the specimen is presented in figure 1. The Von Mises stress criterion was selected to present the effect of lateral /confining/ pressure. Both figures were prepared by performing linear elastic finite element (FE) analysis in the ABAQUS software. The FE modeling input parameters were following: Asphalt mixture /E=308MPa, ν=0.4/, Steel /E=210GPa, ν=0.3/. Contact properties between asphalt mixtures and steel were set as hard normal behavior with the tangential friction coefficient equal to 0.09 (Zak & Valentin, 2013). The steel insert was loaded by 1850N.
It should be noted that during specimen mounting in the UST device gluing is not needed,unlike the SST. The UST sample mounting is therefore quicker and less costly. By omitting the specimens gluing process the measured properties variance is not affected by the variation of glue type or operator experience.

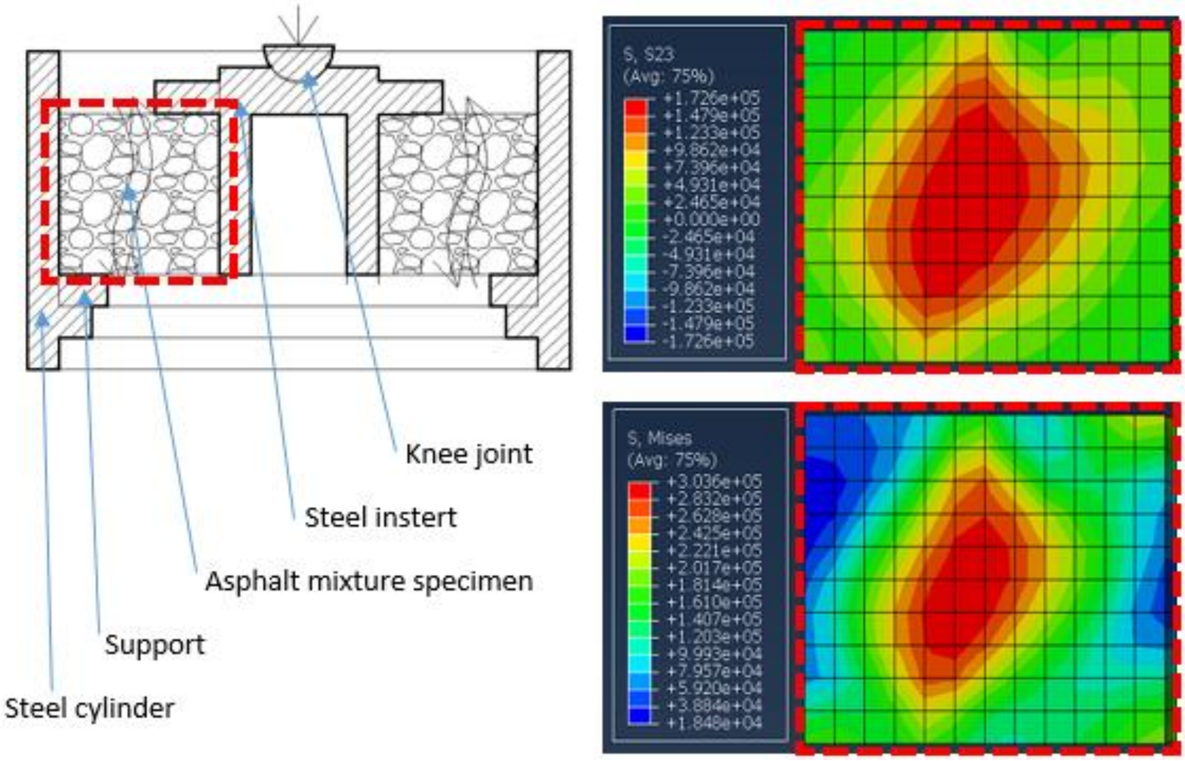

Figure 1: Uniaxial Shear Tester /cross section, shear stress [Pa], Von Mises stress [Pa]/

Figure 2: Uniaxial Shear Tester / top view, hollow cylindrical specimen, UST placed in UTM chamber/

2.1 Specimen preparation and material specification

SST and UST specimens taken from the pavement and specimens prepared in the laboratory were tested during this research project. Blocks were sawed from a pavement test section at UCPRC, Davis. Cylinders were cored from the blocks and the final specimens were cut from a specific asphalt mixture layer using a double bladed saw, which ensured parallel specimen faces. For SST, the cut specimens were glued to steel platens and tested in accordance with [13]. For UST, a hole 50mm in diameter was cored in the center of the cylinders.
Laboratory specimens were prepared with the Superpave Gyratory Compactor. A cylinder 135mm high and 150mm in diameter was produced. Such an “ingot” was further cut in double blade saw, which yield two test specimens. Preparation of the specimens for testing was the same as for the specimens taken from the pavement. The final hollow cylinder is 150mm in external diameter, 50mm thick with the cored 50mm hole in the center.
Five asphalt mixtures were used during the research project. Mix #1 was 19 mm hot mix asphalt (HMA) containing 4.8% of the PG 64-10 neat asphalt binder, 25% of reclaimed asphalt and 0.9% of hydrated lime as an anti-strip additive. The material was prepared in the asphalt plant and batches of the material were taken from the construction site. Mix #2 was 19 mm HMA containing 5% of the PG 64-28PM polymer modified asphalt binder and 15% of reclaimed asphalt and 0.9% of hydrated lime. Mix #2 was also prepared in the asphalt plant and taken from the construction site. Mix #3 was 12.5 mm gap-graded rubberized hot-mix asphalt, RHMA-G, with 7% of the PG 64-10 asphalt binder and a 4% air void content. Mix# 3 was also prepared in the asphalt plant. Blocks of Mix #3 were taken from the UCPRC test section and the specimens were prepared using the above described procedure. Mix #4 was ACO 11+ 50/70 (designated in accordance with [23]), the asphalt concrete mixture used for wearing courses with 5.6% of an asphalt binder of the 50/70 penetration grade. The air void content was 3.5% and the mix design was done in accordance with [23]. Mix #5 was prepared from the same material as Mix #2 but with the targeted 96% degree of compactionrelative to briquette bulk specific gravity [24]. The average specimen’s air void content was 7.6%.
The testing matrix was designed so that the validation of the measured asphalt mixture properties was done over a broad range of mixture properties. Thus, it covers:

- Samples taken from the pavement and samples prepared in the laboratory,
- polymer modified, rubberized and conventional binders,
- the mix design according to Czech amend to European specification and Caltrans material specifications,
- well compacted and poor compacted mixtures,
- variety of aggregate sources.

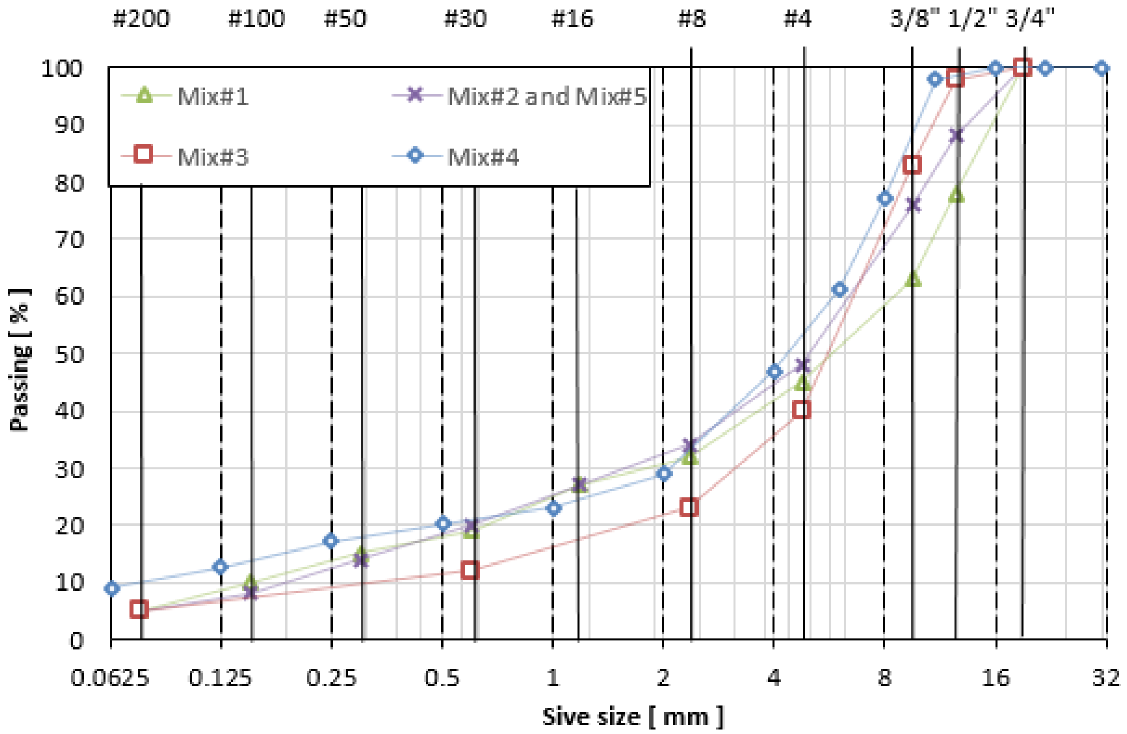

Figure 3: Asphalt mixture grading curve

3. EXPERIMENTS

The main purpose of the laboratory testing was to first obtain data from the newly developed UST device and, second to statistically evaluate the similarities between the UST device and the currently used SST. Five replicates were tested for each asphalt mixture and in case of repeated shear tests and three in case small amplitude oscillation tests.

3.1 Specimen preparation and material specification

Repeated loading seems to be the most suitable material testing approach to determine the asphalt mixture resistance to permanent deformation. The suitability of the analysis determining the portions of recoverable and non-recoverable strains changing over time with the application of repeated loading and unloading has been demonstrated by many researchers [8], [25]–[27]. The Repeated Simple Shear Test at Constant Height /RSST-CH/ was performed in accordance with [13]. The equivalent test procedure, Uniaxial Repeated Shear Test /URST/, compound from 30,000 cycles containing haversine shear pulses 69kPa for 0.1s followed by 0.6s of rest periods, was developed and performed for the same number of samples using UST. The test temperature was maintained at 50°C.
An example of mined test data from URST is presented in Appendix A. As can be seen from the presented figures, all measured characteristics have a very low scatter. The resilient moduli, relative peak strain and permanent strain increments reach their steady state values for most of the cases after 100 to 300 loading cycles. Also, the absolute peak strain and accumulated permanent steady state increments reach their steady state increments after the first 100 to 300 loadings. The typical trend of shear strain of five replicates is presented in last figure.
The correlation between the parameters developed from RSST-CH /SST/ and URST /UST/ test results are presented in Figure 4. The resilient modulus was determined as a portion of shear stress and relative peak strain at 100th cycle. Even if the shear resilient modulus may not be a good rutting performance indicator [28], the shear resilient moduli of the asphalt mixtures reached their steady state after 100 cycles thus such a value can be considered as a representative elastic characteristic for the pavement strain calculation. The correlation coefficient of linear regression between the resilient moduli values measured by RSST-CH and URST was equal to 0.71.
Asphalt mixtures accumulated shear strains have been fitted with a second order polynomial function. The same parameters of the polynomial function can be obtained from the linear fitting in the log-log scale. The slope of such a fitted curve, in the secondary phase, is called the m-value and has been found to correlate well with the field rutting

performance parameters [29]. The correlation between UST and SST m-values is presented in figure 4 and the correlation coefficient is 0.82.
One of the quality measures relating the pavement rutting performance to in laboratory measured characteristics is also the number of cycles to 5% permanent shear strain which SHRP research indicated corresponded to a 12.5 mm rut depth (Monismith et al. 1994). To capture one more point from the accumulated permanent shear strain, the number of loading repetitions to 3% was also studied. The usability of such a parameter for the pavement rutting performance was shown in WesTrack and I-710 projects [6], [9]. The statistical relationship can be expressed with very good correlation coefficients equal to 0.98 and 0.84 respectively.
The Weibull curves can be applied for the regression of accumulated permanent shear strain [30], [31]. Firstly, the three stage Weibull approach has been utilized for the measured data analysis. The determined accumulated permanent shear strain does not exhibit the tertiary stage rutting either in the case of the RSST-CH or in the case of the URST. Therefore, the two stage Weibull approach has been found to be appropriate for both. The exponent of the Weibull regression second phase was determined for RSST-CH and URST. The measure of linear correlation is a correlation coefficient equal to 0.93.
Looking at the overall material performance, Mix #1 19mm HMA with the PG64-28PM polymer modified asphalt binder has the best material performance in regard of resistance to permanent deformation. The second best quality was obtained by Mix #2 19 mm HMA PG64-10. Even if Mix #5, 3/4"HMA PG64-28PM 96%DC, was compacted only to 96% of bulk specific gravity, it is placed in the imaginary third position among the studied materials' rutting susceptibility. It also shows the high resistance of polymer modified asphalt binders to permanent deformation. Through determined material characteristics close to each other, a stronger rutting potential of mixes #3 and #4, RHMA-G PG64-10 and ACO 11+ 50/70 was identified. The described sequence of material characteristics can be concluded from all the presented charts and studied material characteristics except for resilient moduli. It suggests that the resilient modulus may not be a good rutting performance indicator [28].

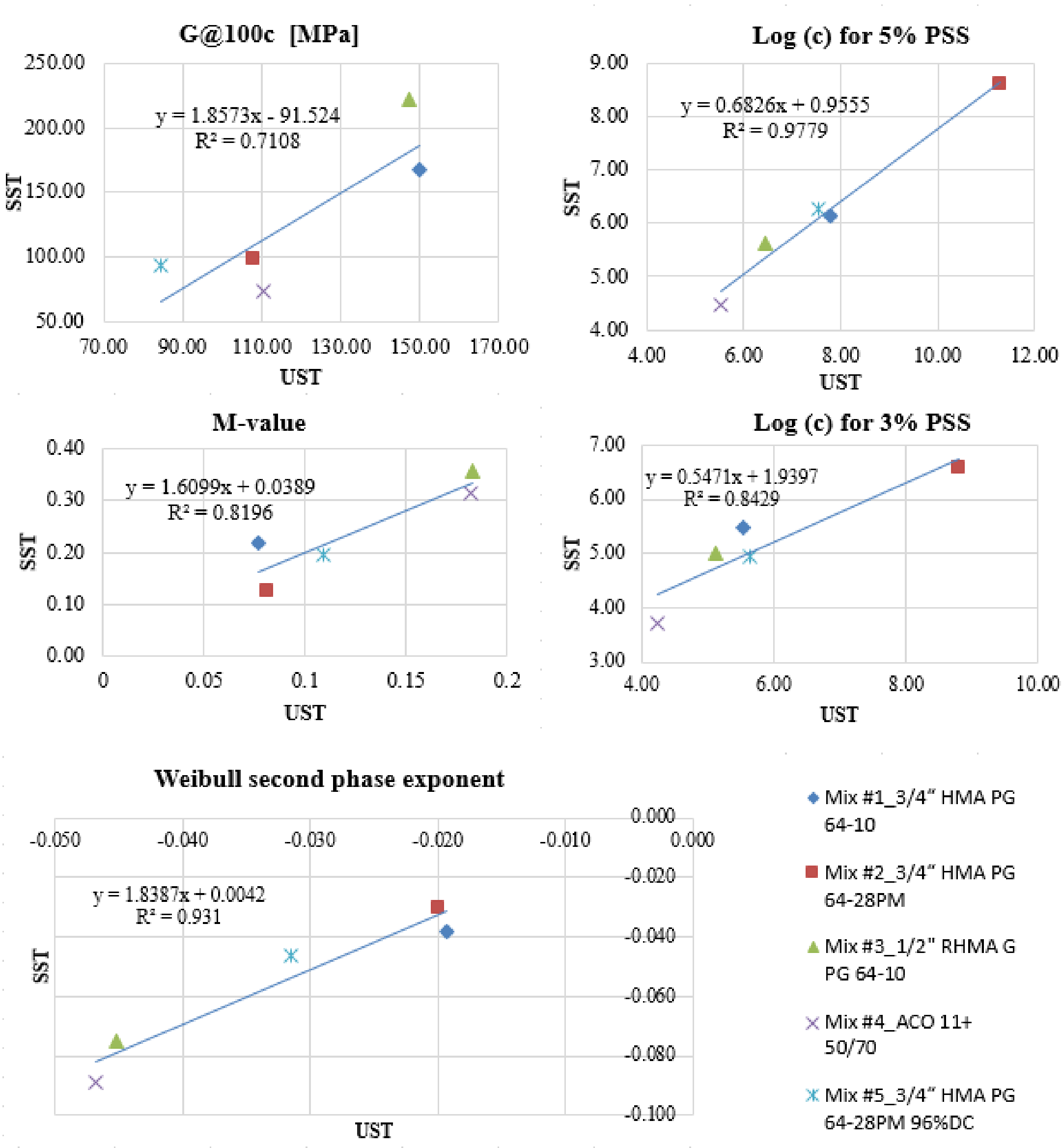

Figure 4: Correlation between SST and UST

3.1.1 Variability

The variability of both the RSST-CH and URST test was studied. The calculated means are presented in Figure 4. To study the dispersion from the mean, the standard deviation was computed. The standard deviation is one of the repeatability measures. The standard deviation was calculated for each asphalt mixture type and the average standard deviation as the in laboratory test repeatability is presented in the last column of table 1. The standard deviations (SD) of the measured resilient modulus and the m-value for the URST test are smaller and higher for cycles to 5% Permanent Shear Strain (PSS), respectively, as can be seen from table 1.

Table 1: Correlation between SST and UST

UST		Mix #1	Mix #2	Mix #3	Mix #4	Mix #5	Average
Standard deviation	Resilient modulus	9	19.7	16	8.1	12.1	**12.98**
	M-value	1.70E-02	2.00E-02	3.10E-02	2.10E-02	2.00E-02	**0.02**
	5% PSS	1.20E+08	1.20E+11	3.00E+06	2.10E+05	2.90E+10	**2.98E+10**
Coefficient of variation	Resilient modulus	0.06	0.18	0.11	0.07	0.10	**10.4%**
	M-value	0.22	0.25	0.17	0.07	0.18	**18.0%**
	5% PSS	1.91	0.64	1.08	0.60	1.01	**104.9%**
SST		Mix #1	Mix #2	Mix #3	Mix #4	Mix #5	**Average**
Standard deviation	Resilient modulus	16.2	11.7	92.6	10.1	28.1	**31.74**
	M-value	4.60E-02	1.50E-02	4.10E-02	3.20E-02	3.10E-02	**0.033**
	5% PSS	6.70E+06	2.10E+09	1.50E+05	2.40E+04	4.90E+08	**5.19E+08**
Coefficient of variation	Resilient modulus	0.10	0.12	0.42	0.14	0.21	**19.5%**
	M-value	0.21	0.12	0.11	0.10	0.12	**13.4%**
	5% PSS	1.49	2.15	0.82	0.81	1.29	**131.0%**

3.2 Shear Frequency Sweep (Small Amplitude Oscillation)

A sinusoidal load is applied onto the tested sample in the perpendicular direction to the tested cylindrical sample axis during the Shear Frequency Sweep Test at Constant Height /SFST-CH/ in accordance with [13]. The applied loading passes through zero to alternately positive and negative values and the delayed material response is measured.

The Uniaxial Shear Frequency Sweep Test /USFST/, run in UST, has a different form in the case of small amplitude oscillation testing than in SFST-CH. The loading is applied on the sample in the direction of the tested hollow cylindrical sample axis, the same direction as that in which the specimen is compacted and loaded by traffic. The load pushes the steel insert through the specimen exciting the shear load in the tested sample. Therefore, the applied loading varies from zero to positive values and the delayed material response is not affected that the machine would pull back the steel insert.

Ideally, Small Amplitude Oscillation Tests were executed in the controlled strain mode with the strain amplitude set within the linear viscoelastic range. However, the desired sinusoidal shape of the applied stress was poorly attained and the tuning of the Proportional-integral-derivative /PID/ controller will have to become a necessity for each individual test. The reason seems to be that the material properties become part of the machine control loop. The displacement response was generated through material properties, consequently the PID values for the machine loop control are dependent on the material properties in the controlled strain mode.

Thus, the controlled stress mode has been found as an appropriate solution to overcome the obstacles with the PID value tuning in the control signal loop of the strain mode. The settings of the SFST-CH were established in previous work [32]. First, SFST-CH was performed. The same SFST-CH settings as in [32] were used in this article. Further, the data were analyzed and from the tests performed on asphalt mixtures #1, #2 and #3 average stresses with dependences on temperature and frequency were computed. The SFST-CH stresses were afterwards fitted with the s-type function, [33], and the stresses were calculated for the use in USFST performed in UST. More details about stress fitting of small amplitude shear oscillation can be found in [21].

Both asphalt mixture shear frequency sweep tests were done in a broad range of temperatures from -15°C to 75°C and a frequency domain of 0.01 - 10Hz in the case of SST and 0.01-40Hz in the case of UST. The Time-Temperature Superposition /TTS/ was performed for all the asphalt mixtures at the reference temperature of 15°C. The reduced frequency $\omega' = a_T * \omega$ was described by the Williams-Landel-Ferry relation. No vertical shifting was needed for all the studied TTS mixes. Both the phase angle and the shear moduli were shifted with the same horizontal shift factors.

The typical behavior of the measured asphalt mixture characteristics is shown in figure 5 for Mix #1 / 3/4"HMA PG64-28PM / master curve. All the tested mixes displayed a similar behavior, i.e. the complex shear modulus, G*, starts from its plateau at low frequencies and increases with reduced frequencies. The G* also reaches its plateau at high frequencies / low temperatures in the case of USFST. The absolute maximum of G* was not even found at -15°C in the case of SFST-CH. The real part of the shear modulus, G', and the loss shear modulus, G'', reaches its absolute maximum in the displayed domain of reduced frequencies in the case of USFST. Similarly, the loss tangents of all the materials reached their absolute maximum well before their moduli did in the case of USFST. The G* positively correlates between both tests. The variation in the trends of a real part of the shear modulus, G', and the loss modulus, G'', is caused by the negative correlation of the phase angle.

It must be emphasized that the different trend of the phase angle was found in previous work [32]. If the trend of the phase angle, measured by SFST-CH from [32] is utilized in this article, the phase angle will be positively correlating with the trend of the phase angle measured by the USFST presented in this article. Such an assumption will resolve the difference in phase angle trend. From the behavior of dynamic material functions, it is clear that all the materials behave as linear viscoelastic solids (in the tested domain). This can be clearly seen in figure 5, where there is no upturn in tg(δ) to the higher values for the behavior of the loss tangent at the lowest reduced frequencies (highest temperature), usually indicating the flow of the material [4].

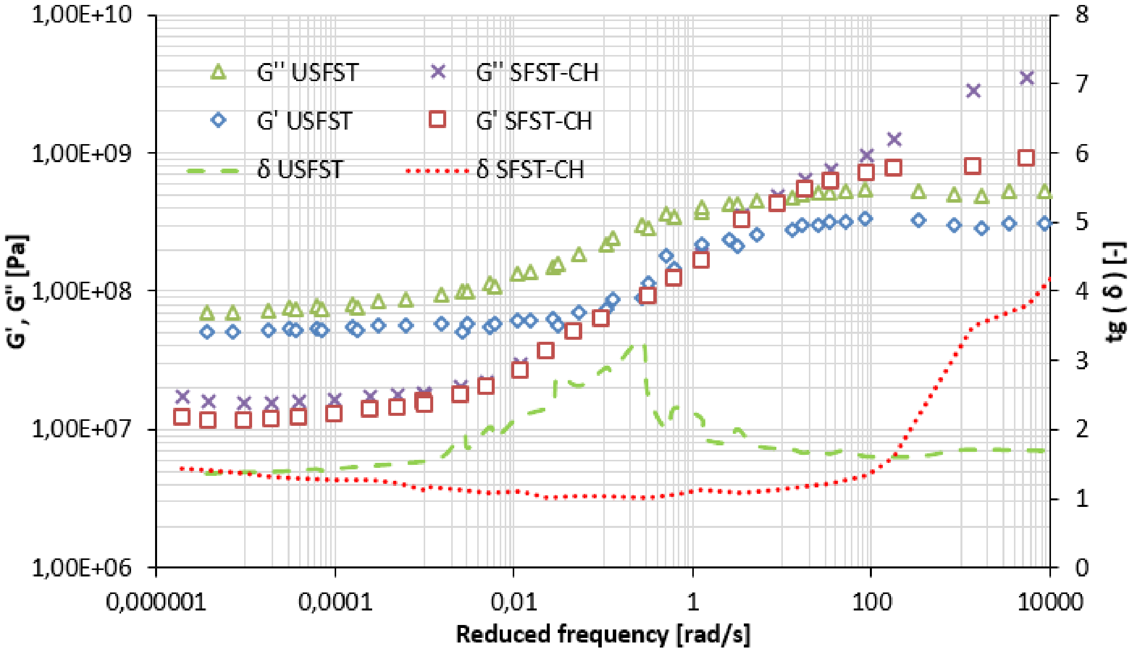

Figure 5: Mix #1 / 3/4"HMA PG64-28PM / master curve

4. Conclusions

The results from two test devices and two test methodologies performed are presented in this article. The main focus of the paper is to present measured data from the newly developed Uniaxial Shear Tester and to assess the correlation with the established Superpave Shear Tester developed in 1990s. The correlation is presented through the linear correlation of determined material properties. It can be concluded that all the measured characteristics have, statistically speaking, a very good correlation for repeated shear tests. The correlation coefficients are higher than 0.7, namely the resilient shear modulus –0.71, the logarithm of cycles to 5% permanent shear strain - 0.98, the logarithm of cycles to 3% permanent shear strain – 0.84, the m-value - 0.82 and the Weibull second phase exponent 0.93. The test result's variability may be considered as similar, or slightly lower in the case of UST, for selected material characteristics.

The other test methodology discussed in this paper is the Small Amplitude Oscillation Shear Test, also referred to as the Frequency Sweep Shear Test. It was found that the complex shear moduli measured by UST and SST devices positively correlate (R > 0) over the measured domain. The phase angle does not exhibit the same positive correlation. It may be caused by the different way of loading discussed in the introduction of paragraph 3.2.

The UST device is a simpler and lower cost alternative to SST device and has promising value to the community because it allows performance testing of as-built pavements for rutting susceptibility and in laboratory asphalt mixture shear properties determination.

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