Research Article

# Hot mix asphalt (HMA) moisture susceptibility analysis: material loss to mechanical properties

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**Abstract**

Numerous studies have been conducted to identify moisture sensitive mixes during mix design by simulating various mechanisms of moisture damage. These methods involve the determination of changes in strength or stiffness of asphalt mixes due to moisture conditioning. The objective of this study is to understand the coupled problem of moisture induced material loss and change in strength/stiffness of the mix. Moisture Induced Stress Tester was used for conditioning samples of a poor and a good performing mixes. This test applies cyclic pressures in the asphalt mix samples through repeated pulses of water. The effluent containing aggregates and binder that were dislodged from the samples during the moisture conditioning process were collected for testing. Both coated and uncoated/fractured aggregates were found in the effluent. The results indicated that the samples with a higher loss of asphalt binder compared to other samples in the investigation during conditioning may exhibit higher tensile strengths, and those with a loss of finer materials, which is indicative of aggregate breakdown, show a lower tensile strength. Both seismic modulus and indirect tensile strength tests were found to be able to differentiate the poor and good performing mixes. For the mixes used in this study, the rate of change in indirect tensile strength during moisture conditioning was found to be strongly correlated to the pre-conditioning modulus of the mix, and a method is suggested for using the threshold values of properties of pre-conditioning mixes for different durations of moisture conditioning during mix design to screen poor mixes in a fast and nondestructive manner.

**Keywords** HMA · Seismic modulus · Indirect tensile strength · Dissolved organic carbon · Moisture induced stress tester · Moisture damage · Loss of aggregates · Loss of asphalt binder

## 1 Introduction

Most of the common tests that are conducted for the evaluation of moisture susceptibility of hot mix asphalt (HMA) consist of a conditioning process and a mechanical test [1]. These tests predict the moisture susceptibility in terms of loss in mechanical properties, or retained strength. However, moisture induced damage may also include loss of material—dislodgement of aggregates and loss of binder compounds, which could have an influence on the loss of mechanical properties or performance of the mixes. Though there was no comprehensive study reported in this regard, a previous study had identified the physical and chemical changes of asphalt binder from moisture conditioning [2]. The present study is conducted to evaluate the use of Moisture Induced Stress Tester (MIST), assess the loss of materials and change in mechanical properties as a potential approach for identifying moisture susceptible HMA during mix design. A combination of two approaches including using the effluent water from water

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conditioning process that was collected and using a non-destructive testing equipment was adopted in this study.

### 1.1 Background

MIST is a relatively new device that was developed to simulate moisture induced damage in the laboratory [3]. The equipment consists of a chamber with an air pressurized bladder and inlet from a water tank as shown in Fig. 1. The HMA sample is placed inside the enclosed chamber which is filled with water. When the machine is started, the bladder at the bottom of the chamber inflates and deflates repeatedly, and the sample is subjected to cycles of pressurized water. This process simulates the repeated action of traffic loading under moisture conditions in the wheel-path [4]. The MIST conditioning simulates the moisture induced damage in the field, and such conditioned samples are tested for their mechanical properties.

Various studies have reported the efficiency of MIST to characterize moisture susceptible mixes similar to or even better than the currently practiced method of AASHTO T 283 [5, 6]. The intensity of moisture induced damage simulated by MIST was found to be a function of the number of cycles and the duration of pre-MIST dwell. The intensity of moisture induced damage simulated by MIST was found to be a function of the number of cycles and the duration of pre-MIST dwell time (dwell time is the time when samples are immersed in water prior to the conditioning cycles). Tarefder et al. [7] found significant damage when doubling the cycles from 3500 to 7000. Varveri et al. [8] reported a greater reduction of strength of the mix with longer pre-MIST dwell period. Indirect tensile strength test (ITS), superpave simple performance tests (SPT), superpave indirect tensile test (IDT), dynamic modulus test, Ultrasonic pulse velocity test are some of the mechanical tests which have the potential to be combined with the MIST conditioning process for the identification of moisture susceptible mixes [5, 9, 10]. Tarefder and Ahmad [9] have studied the effect of pore structure on moisture damage using the MIST and found that permeable pore had a good correlation with permeability of asphalt samples but did not contribute much to the moisture damage. Using the MIST, Shu et al. [10] have found a similar performance of HMA and WMA, and high resistance of mixes with RAP against moisture induced damage [11]. Recently, an ASTM standard D7870-13 [12] has been developed for the MIST conditioning process.

A few studies have reported the observation of loss of materials during moisture conditioning in the laboratory. Varveri et al. [8] reported fine aggregates and Zofka et al. [11] reported traces of asphalt binder in the water that has been collected from the conditioning process. Studies have also reported the leaching of Poly Aromatic Hydrocarbons (PAH) from asphalt mixes [13, 14] under the impact of water conditioning, though the amounts are very low. Song et al. [15] conducted a study to determine

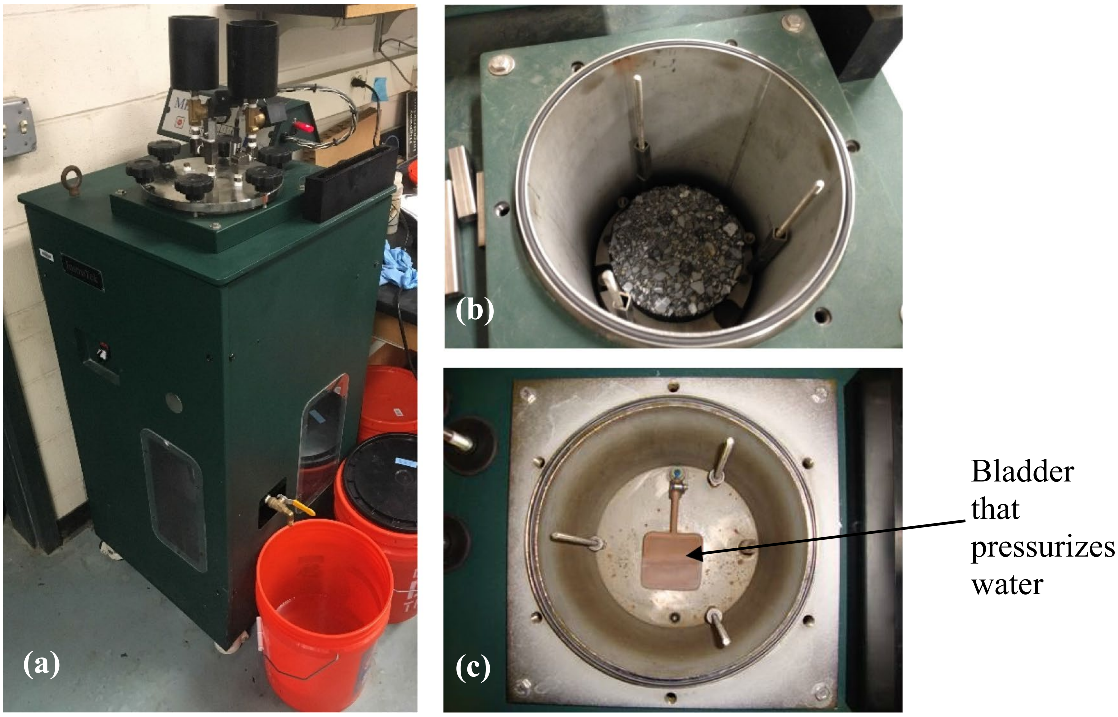

**Fig. 1** A typical picture of Moisture Induced Stress Tester (MIST): **a** MIST machine, **b** MIST chamber, **c** MIST bladder

the chemical composition of water-soluble compounds in asphalt and have listed various organic compounds and their respective proportions that varied with the asphalt source and mix aging methods that were used.

A number of studies have been conducted with the use of nondestructive tests (NDT) on HMA. As early as in 1960s, Stephenson [16] have used the compression wave velocity technique to study the change in dynamic properties of HMA in the transitional temperature regime; it was later taken up by the researchers in the 20th century and after which it was considered as one of the useful non destructive techniques to determine the properties of HMA mixes. Celaya and Nazarian [17] and Rojas et al. [18] have developed quality control guidelines for the construction of HMA layers with the use of NDT. Rojas et al. [18] evaluated HMA mixes in the laboratory using ultrasonic pulse velocity (UPV) test and concluded that the seismic modulus increases with a decrease in the voids in the total mix (VTM) and decreases with a decrease in the binder viscosity; however, the impact of the viscosity was found to become less pronounced as the VTM increased. Norambuena-Contreras et al. [19] have examined two types of mixes—dense and porous using the ultrasonic direct test to determine dynamic modulus. The authors identified the difference in transmission time between two types of mixes due to the difference in porosity, which resulted in longer propagation times for the porous mix. Birgisson et al. [20] evaluated the ultrasonic pulse wave velocity test for monitoring moisture damage effects in asphalt mixtures and also studied the effects of saturation levels, aggregate structure and aggregate type on mixture conditioning. The results demonstrated the sensitivity of seismic modulus to effects of moisture damage and a decrease in modulus was observed with an increase in the level of saturation. A visual investigation of failed specimens indicated a cohesive and adhesive failure, and breakage of aggregate failures for conditioned dense graded, granite aggregate mixes. Arabani et al. [21] evaluated the effect of various HMA mix parameters with the UPV, which was found to be sensitive to changes in the asphalt content, filler content, percent of fractured particles, gradation type and compaction method of the HMA. Though various researchers have studied the effect of moisture on asphalt mixes, a comprehensive study to understand the moisture susceptibility of hot mix asphalt (HMA) in relation to strength, stiffness and material loss was not carried out.

### 1.2 Objective

The objective of this study was to understand the impact of moisture susceptibility of hot mix asphalt (HMA) mixes on strength, stiffness and material loss, and thereby deduce a method to utilize these properties to detect moisture susceptible HMA mixes.

## 2 Materials and methods

### 2.1 Materials and mixes

Two different types of aggregates and one asphalt binder, procured from the Maine Department of Transportation (DOT) were used to prepare samples. All samples were compacted to 7 ± 1% voids in total mix (VTM), with a Superpave gyratory compactor, using gradation and asphalt binder content that is used by Maine DOT for producing regular mixes. One mix, prepared with the "PI" aggregate has been identified as a poor performing mix (evidence of moisture-induced loss of materials and deterioration of layer), on the basis of field observation and tests with Hamburg rut tester [22], whereas the other "SM" mix has been identified as a good performing mix. Table 1 shows the relevant mix design information for the two mixes.

Apart from testing for bulk specific gravity and theoretical maximum gravity (for mixes) to calculate voids in total mix (VTM, %), the testing of mixes consisted of pre-MIST and post-MIST determination of Seismic Modulus ($E_s$, MPa) and indirect tensile strength (ITS, kPa), and post-MIST testing of loss of materials (LOM, gram). Samples of the effluent water were subjected to dissolved organic carbon (DOC, ppm)

**Table 1** Details of mix design

| Design parameter/mix type | PI | SM |
|---|---|---|
| Nominal maximum aggregate size (NMAS) (mm) | 12.5 (Coarse-graded) | 12.5 (Fine-graded) |
| Number of gyrations ($N_{design}$) | 50 | 75 |
| Asphalt binder grade | PG 64-28 | PG 64-28 |
| Asphalt content (%) | 5.9 | 5.4 |
| *Gradation* | | |
| Sieve size (mm) | % Passing | |
| 19 | 100 | 100 |
| 12.5 | 90–100 | 90–100 |
| 9.5 | 78–90 | 74–88 |
| 4.75 | 64–78 | 43–57 |
| 2.36 | 38–46 | 31–39 |
| 1.18 | 23–31 | 20–28 |
| 0.6 | 14–20 | 13–19 |
| 0.3 | 8–12 | 8–12 |
| 0.15 | 5–9 | 5–9 |
| 0.075 | 3.9–6.0 | 3.5–7.0 |

analysis to detect traces of asphalt binder in the effluent and determine their content. The testing utilized a Shimadzu TOC-5000A analyzer, which uses combustion of carbon to $CO_2$ and analysis with a non-dispersive infrared (NDIR) gas detector to quantify total carbon.

## 2.2 Moisture conditioning

In the MIST conditioning process, first the cylindrical samples compacted with a gyratory compactor are placed in a conditioning chamber in the MIST and the chamber is filled with water. The water can be maintained at a specific temperature, and the sample can be kept in the water for a specific period of "dwell" time. The moisture conditioning process used in this study consisted of 20 h of dwell time at 60 °C and 10,000 cycles at 207 kPa and 60 °C. Every 1000 cycles take approximately 1 h. At the end of the conditioning process, the samples are taken out and subjected to post-MIST condition testing such as Es, ITS, LOM and DOC. Note that since this is a simulative test, the number of cycles used in the MIST was selected so as to cause significant (detectable) damage in poor performing mixes, as found from other studies [7, 8, 22].

## 2.3 Tests

The Seismic Modulus testing was conducted using an ultrasonic pulse velocity (UPV, V-meter) tester with 150 kHz transducers (ASTM C597-16 [23]). The time for travel of the wave was noted from testing and then utilized in the following formulae to calculate $E_s$.

$$V_p = \frac{H}{t_v}. \tag{1}$$

$$M_V = \rho \times V_p^2. \tag{2}$$

$$E_s = M_V \times \frac{(1+\mu)\times(1-2\mu)}{1-\mu}. \tag{3}$$

where, $V_p$ = velocity of wave; $t_v$ = time of travel; ρ = density; μ = Poisson's ratio, considered to be 0.35.

Indirect tensile strength tests were carried out with a compressn testing machine using a loading rate of 50 mm per minute, and the following formula was used for the calculation.

$$\text{Indirect tensile strength (ITS), kPa} = \frac{2P}{\pi \times t \times d}. \tag{4}$$

where, P = failure load in N; t = thickness, mm; d = diameter, mm.

The effluent from the MIST conditioning process was collected at the completion of the 10,000 cycles. The aggregate particles found in the effluent were collected and checked for gradation by sieve analyses, from which the fineness modulus (ASTM C125-16, [24]) was estimated. Samples of the effluent water were subjected to dissolved organic carbon (DOC) analysis to detect traces of asphalt binder in the effluent and determine their content. The testing utilized a Shimadzu TOC-5000A analyzer, which uses combustion of carbon to $CO_2$ and analysis with a non-dispersive infrared (NDIR) gas detector to quantify total carbon.

# 3 Results and analysis

Table 2 shows the results of volumetric and mechanical properties, and loss of material from MIST conditioning. It can be seen from the VTM results that there was a slight increase in air voids due to moisture conditioning for both mixes PI and SM. DOC is observed to have a positive correlation with post-MIST ITS based on the PI and SM mix pooled data (Fig. 2). The correlation in Fig. 2 can be explained by the fact that a higher DOC indicates a

**Table 2** MIST conditioning results–volumetric and mechanical properties, and loss of material

| Mix ID | Volumetric and mechanical properties | | | | | | loss of material | |
|---|---|---|---|---|---|---|---|---|
| | Before MIST conditioning | | | After MIST conditioning | | | | |
| | Voids in total mix, VTM (%) | Seismic modulus, $E_s$ (MPa) | Indirect tensile strength, ITS (kPa) | Voids in total mix, VTM (%) | Seismic modulus, $E_s$ (MPa) | Indirect tensile strength, ITS (kPa) | Fineness modulus (FM) | Dissolved Organic Carbon (DOC), ppm |
| PI | 6.9 | 12,803 | 717 | 7.5 | 12,419 | 456 | 1.56 | 0.944 |
| PI | 6.5 | 13,437 | 720 | 7.6 | 12,545 | 528 | 0.97 | 1.090 |
| PI | 6.4 | 13,551 | 681 | 6.8 | 12,895 | 566 | 1.96 | 2.186 |
| SM | 7.6 | 13,222 | 644 | 9.5 | 13,126 | 478 | 3.73 | 0.856 |
| SM | 7.2 | 14,427 | 615 | 7.2 | 13,392 | 597 | 2.51 | 1.553 |
| SM | 6.7 | 14,522 | 601 | 6.9 | 13,909 | 616 | 2.86 | 2.927 |

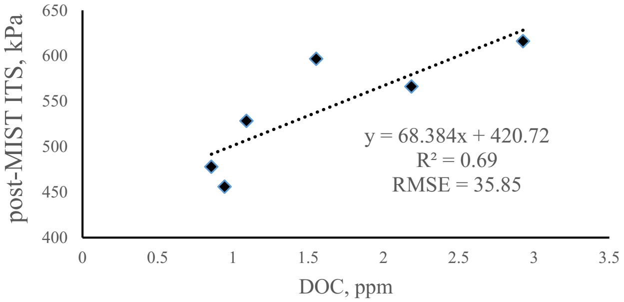

**Fig. 2** Plot of DOC Vs. post-MIST indirect tensile strength (ITS)–pooled data

higher loss of asphalt binder from the mix, and mixes with reduced asphalt content are expected to be at a higher tensile strength. This observation is important since in many cases designers rely on the retained strength or the post conditioning strengths only, to evaluate the mix's resistance against moisture damage. While this is a reasonable approach, it should be used with caution since, a loss of the binder, which is a precursor to more severe damage of loss of aggregates and gradual loosening of the mix in the field, may falsely indicate a high resistance against moisture damage after the laboratory conditioning process.

The fineness modulus (FM) of the aggregate material lost during the MIST conditioning shows a negative correlation with change in indirect tensile strength as a result of MIST conditioning (Fig. 3). This is because, a lower FM indicates a finer gradation, and a finer gradation indicates more breakdown of larger aggregates, which would have a higher weakening effect on the strength of the mix. It is noted that a gradation that is finer than the original gradation means that fine aggregates have been generated during the MiST conditioning process. Since there was no other source of fine aggregates, these additional fine aggregates must have come from the breakdown of larger aggregates in the mix. A higher FM most likely means that larger size aggregates are displaced by moisture, as whole particles, and there is a relatively less aggregate breakdown in the mix. This is evident from a higher FM for the materials lost by the SM mix, as compared to that of the PI mix. Note that an outlier was removed from the dataset, which improved the correlation significantly.

The rate of change in ITS was seen to have a good correlation with the pre-MIST $E_s$ (Fig. 4). It is noted that the rate of change in ITS per hour was determined as a ratio of loss in ITS due to MIST conditioning and the time taken for MIST conditioning cycles. For example, a loss in ITS of 261 kPa for a conditioning time of 10 h (1000 cycles per hour and a total of 10,000 cycles) results in a rate of change in ITS of 26.1 kPa/h. This can be explained by the fact that mixes with higher stiffness experience lower strain under the applied stress in the MIST and are hence less susceptible to deterioration of the mix. Equation 5 shows the relation, developed from the pooled data from SM and PI mixes.

$$Rate\ of\ Change\ in\ ITS,\ kPa,\ per\ hour = 219.21 - 0.0151 \times (pre - MISTE_s) \tag{5}$$

$R^2 = 0.95$; were $E_s$ = pre-MIST Seismic Modulus, MPa

This equation can be utilized to estimate the loss of ITS throughout the design life of the pavement, if the number of hours the pavement is subjected to moisture is known. The data can then be utilized to estimate the minimum initial $E_s$ that is required to ensure a minimum ITS of the mix throughout the design life. For example, determining the estimated loss during the design life, one can choose a mix with the required amount of ITS during construction, such that even after loss due to moisture damage, the mix remains sufficiently strong for adequate performance. The relationship presented in Eq. 5 can be explained as follows. The change in tensile strength in mixes during the conditioning process is due to the growth of cracks formed by the repeated cycles of loading of the sample

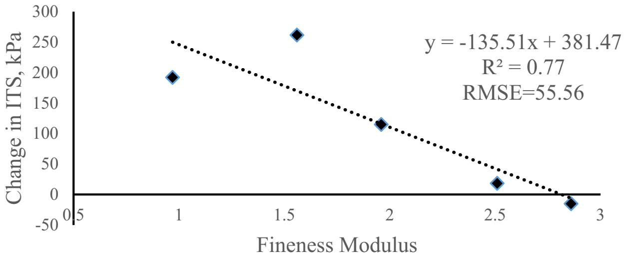

**Fig. 3** Plot of fineness modulus versus change in indirect tensile strength (ITS)

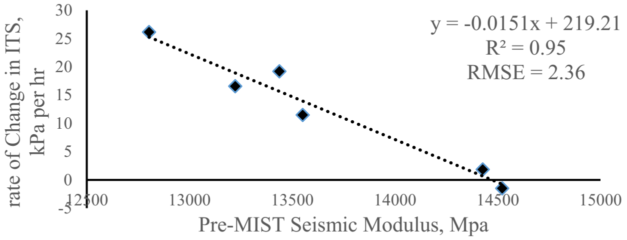

**Fig. 4** Plot of pre-MIST seismic modulus versus rate of change in indirect tensile strength (ITS)

in water. The dependence of the crack growth rate (at a specific temperature) on the material is exhibited by the relationship between the rate of change in the indirect tensile strength and the pre-conditioning Seismic Modulus value. The equation can also be utilized to estimate the expected change in ITS due to an expected variation in the pre-MIST Seismic Modulus. For the data used in this study, a mean and a standard deviation of 13,660 MPa and 681 MPa were observed for the pre-MIST Seismic Modulus.

Since in general, the variability of $E_s$, due to variabilities in materials and construction, values can be expected in the field, it will be beneficial to evaluate the impact of the variability on the rate of change in ITS. The results will be more practical than a single point value since a confidence interval regarding the resistance of the mix against moisture damage can be determined. To obtain such an estimate of confidence interval, a probabilistic method is generally used. In this case, Monte Carlo analysis was selected as a tool for such a probabilistic analysis. This technique generates a value of the dependent variable, based on a random selection of data from the input variables. The method continues for the specific number of simulations and finally reports the expected distribution of the dependent variable. Utilizing the average and standard deviation values obtained in this study, a Monte Carlo simulation of the change in ITS, was conducted and the results are shown in Fig. 5. The 90% confidence interval for loss of ITS (per hour of moisture conditioning) is −4 to 30 kPa, with a mean of 13 kPa per hour.

Based on the information regarding the relatively poor performance of one of the aggregates (PI) and the better performance of the other (SM), the data were then separated to determine if there was any statistically significant difference between the test results of the two mixes. From the statistical analysis, it was found that there was a significant difference between pre-MIST and post-MIST ITS for the mixes with PI aggregates (poor performing) and no significant difference was found in the case of mixes with SM aggregates (better performing). This showed that mixes with SM aggregates were more resistant to damage caused by moisture conditioning. Similar results were also found for the Seismic Modulus (Table 3). Therefore, the seismic modulus can be suggested as a potential method of screening mixes for their moisture susceptibility—the advantage is that the method is fast and nondestructive. Changes in both ITS and the Seismic Modulus during the conditioning process in moisture susceptible mixes are due to the loss of integrity of the mix, as a result of loss in cohesion or adhesion or breakdown of material. Note that Seismic Modulus has been found to be sensitive to moisture effects [20, 25].

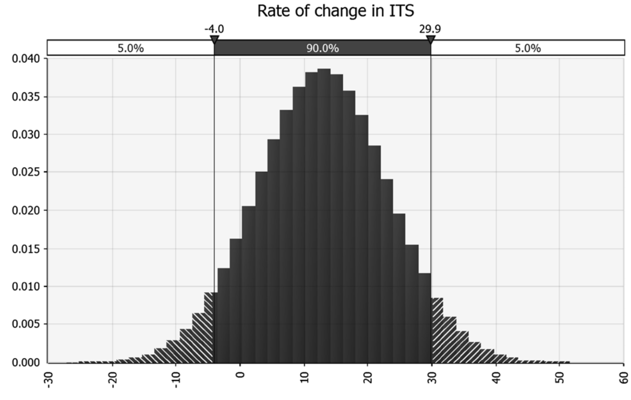

**Fig. 5** Results of Monte Carlo analyses

One more point is that the variability of the seismic modulus is much lower than that of the ITS, as evident from its lower COV specifically in the post-MIST condition which is 1.95 (PI mix) and 2.95 (SM mix) compared to 10.8 (PI mix) and 13.3 (SM mix) for ITS.

### 3.1 Estimation of pre-MIST threshold values

Equation 5 can be utilized to estimate minimum (threshold) values of pre-MIST ITS and seismic modulus ($E_s$) in order to ensure adequate performance throughout the pavement design life. In order to accomplish this, test and field performance (with respect to moisture damage) data from twenty-one mixes were collected from Maine DOT. It was found that the only two poor performing mixes have post-MIST ITS values at or below 500 kPa whereas the good performing ones have > 500 kPa post-MIST ITS values [22]. Hence 500 kPa can be taken as a minimum desirable ITS after the expected number of hours of moisture damage for adequate performance of a mix in the field. Therefore, knowing the number of hours of expected moisture damage conditioning (or exposure to moisture in the field), and taking the minimum value of 500 kPa, it is possible to estimate a threshold value of pre-MIST $E_s$ for different values of Pre-MIST ITS, as shown in Fig. 6.

**Table 3** Results of statistical analyses of seismic modulus and indirect tensile strength data (see Table 2 for the data)

| Hypothesis test | Inference @ 5% significance level |
|---|---|
| Mix: PI | |
| Paired sample: (pre-MIST $E_s$–post-MIST $E_s$) | Different |
| ANOVA: (pre-MIST ITS vs post-MIST ITS) | Different |
| Mix: SM | |
| Paired sample: (pre-MIST $E_s$–post-MIST $E_s$) | Not different |
| ANOVA: (pre-MIST ITS vs post-MIST ITS) | Not different |

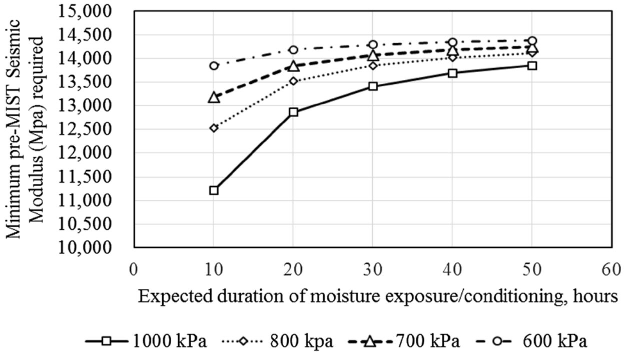

**Fig. 6** Plots of threshold values of pre-MIST seismic modulus versus duration of moisture conditioning for different pre-MIST ITS

The utility of the plots presented in Fig. 6 is as follows. It would be desirable for a mix designer to identify mixes which do not meet the required criteria even before the tests of moisture conditioned mixes are performed. Both MIST conditioning and Indirect Tensile Strength tests are time-consuming, and a desirable option will be to find out that the mix does not meet the minimum retained strength even before the MIST conditioning. Instead of using ITS and MIST first, the mix designer can assume a pre-MIST ITS on the basis of his/her experience with similar mixes, check the seismic modulus of the designed mix (which will take a very short period of time and is nondestructive) and then utilize the chart to determine whether the Seismic Modulus meets the minimum value for the specific time of conditioning. Then the same samples could be utilized for pre-MIST indirect tensile strength tests or post-MIST Seismic Modulus tests, if the Indirect Tensile Strength test is avoided altogether. If after testing, the strengths are higher than what was assumed, the mix can be assumed to be adequately resistant as the minimum required seismic modulus value decreases with an increase in the pre-MIST ITS, for a specific duration of moisture conditioning. If, however, the strength is found to be lower than the assumed value, the designer can improve the mix design. This will help the agency to reduce the chance of ending up with mixes that fail to meet the minimum post-conditioning ITS requirement, and reduce the time of actual MIST conditioning (Fig. 6).

### 3.2 Conclusions and recommendations

The study reported in this paper demonstrated the use of MIST, and the seismic modulus and indirect tensile strength tests as effective moisture conditioning and testing methods, respectively. The methods can be utilized for detecting moisture susceptible HMA mixes during the mix design process. To minimize the use of samples, the designer can also make predictions regarding the moisture susceptibility on the basis of seismic modulus results alone, since the seismic modulus values were found to be sensitive to moisture induced damage. Furthermore, for the expected number of moisture exposure hours, the designer can also estimate the desirable seismic modulus for a range of dry tensile strengths of the mixes. This process can also help avoid the use of MIST in the preliminary

**Fig. 7** Suggested flowchart for using MIST and seismic modulus (Es)

1. Select aggregates and asphalt
2. Compact samples
3. Determine volumetric properties
4. Estimate optimum asphalt content (OAC)
5. Compact six samples at OAC
6. Test six samples for $E_s$
7. Test three samples for dry ITS
8. For estimated hours of exposure to moisture and dry ITS, if $E_s$ is OK (adequate), then go to next step; if not OK, consider adding antistripping agent and/or different aggregate/asphalt, and repeat from step 5; and if OK, proceed to next step
9. Condition three samples in the MIST
10. Test three samples for $E_s$; if there is no significant difference (at significance level of 5%) between $E_s$ of pre and post conditioned samples, then accept the mix and stop; if there is significant difference then proceed to next step
11. Test three samples for ITS
12. If there is no significant difference between ITS of pre and post conditioned samples, then accept the mix and stop; if not, consider using antistripping agent and/or different aggregate/asphalt, and repeat from step 5

mix selection process, and select a few mixes for more rigorous testing. Figure 7 presents a proposed flowchart for screening moisture susceptible mixes. The following specific conclusions and recommendations are made on the basis of this study.

1. Samples undergoing a higher loss of asphalt binder compared to other samples, during moisture conditioning may exhibit higher tensile strengths.
2. Samples with aggregate particles breakdown will exhibit lower tensile strengths compared to other samples with less/no aggregate particle breakdown.
3. The rate of change in indirect tensile strength during moisture conditioning is strongly correlated to the pre-conditioning modulus of the mix, and a proposed equation can be utilized to estimate the loss of strength for a given mix.
4. Based on pre and post-conditioning tests, both seismic modulus and indirect tensile strength tests were able to differentiate between good and poor mixes.
5. Threshold values of seismic modulus of pre-conditioning mixes for different durations of moisture conditioning can be utilized during mix design to screen poor mixes in a fast and nondestructive manner.

## Compliance with ethical standard

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

## References

1. Solaimanian M, Harvey J, Tahmoressi M, Tandon V (2003) Test methods to predict moisture sensitivity of hot-mix asphalt pavements. In: Moisture sensitivity of asphalt pavements-a national seminar, San Diego, 2003-2-4 to 2003-2-6 2003
2. Ahmad M, Mannan UA, Islam MR, Tarefder RA (2017) Chemical and mechanical changes in asphalt binder due to moisture conditioning. Road Mater Pavement Des. https://doi.org/10.1080/14680629.2017.1299631
3. Buchanan MS, Moore V, Mallick R, O'Brien S, Regimand A (2004) Accelerated moisture susceptibility testing of hot mix asphalt (HMA) mixes. In: Paper presented at the 83rd annual meeting of the Transportation research board, Washington
4. Pinkham R, Cote SA, Mallick RB, Tao M, Bradbury RL, Regimand A (2013) Use of moisture induced stress testing to evaluate stripping potential of hot mix asphalt (HMA). In: Paper presented at the 92nd annual meeting of the Transportation Research Board, Washington
5. Chen X, Huang B (2008) Evaluation of moisture damage in hot mix asphalt using simple performance and superpave indirect tensile tests. Constr Build Mater 22(9):1950–1962
6. Mallick RB, Pelland R, Hugo F (2005) Use of accelerated loading equipment for determination of long term moisture susceptibility of hot mix asphalt. Int J Pavement Eng 6(2):125–136. https://doi.org/10.1080/10298430500158984
7. Tarefder RA, Weldegiorgis MT, Ahmad M (2014) Assessment of the effect of pore pressure cycles on moisture sensitivity of hot mix asphalt using MIST conditioning and dynamic modulus. J Test Eval 42(6):1–11. https://doi.org/10.1520/JTE20130095
8. Varveri A, Avgerinopoulos S, Scarpas A (2016) Experimental evaluation of long- and short-term moisture damage characteristics of asphalt mixtures. Road Mater Pavement Des 17(1):168–186. https://doi.org/10.1080/14680629.2015.1066705
9. Tarefder R, Ahmad M (2017) Evaluation of pore structure and its influence on permeability and moisture damage in asphalt concrete. Int J Pavement Eng 18(3):274–283
10. Shu X, Huang B, Shrum ED, Jia X (2012) Laboratory evaluation of moisture susceptibility of foamed warm mix asphalt containing high percentages of RAP. Constr Build Mater 35:125–130. https://doi.org/10.1016/j.conbuildmat.2012.02.095
11. Zofka A, Maliszewski M, Bernier A (2014) Alternative moisture sensitivity test. In: Paper presented at the 9th international conference environmental engineering, Vilnius, Lithuania
12. ASTM D7870 (2013) Standard practice for moisture conditioning compacted asphalt mixture specimens by using Hydrostatic Pore Pressure. American Society for Testing and Materials
13. Brantley AS, Townsend TG (1999) Leaching of pollutants from reclaimed asphalt pavement. Environ Eng Sci 16(2):105–116
14. Kriech A, Kurek J, Osborn L, Wissel H, Sweeney B (2002) Determination of polycyclic aromatic compounds in asphalt and in corresponding leachate water. Polycycl Aromat Compd 22(3–4):517–535
15. Song Y, Wang C, Zhang Y (2011) Determination of the chemical composition in asphalt aqueous solutions by SPE and GC/MS. Pet Sci Technol 29(15):1590–1595
16. Stephenson RW (1968) Temperature effects of the compressional wave velocities of asphalt-aggregate mixtures. Doctoral dissertation, Oklahoma State University, Oklahoma
17. Celaya M, Nazarian S (2008) Implementation of quality management of hot-mix asphalt with seismic methods. Transp Res Rec J Transp Res Board 2057:99–106
18. Rojas J, Nazarian S, Tandon V, Yuan D (1999) Quality management of asphalt-concrete layers using wave propagation techniques. University of Texas at El Paso, Texas
19. Norambuena-Contreras J, Castro-Fresno D, Vega-Zamanillo A, Celaya M, Lombillo-Vozmediano I (2010) Dynamic modulus of asphalt mixture by ultrasonic direct test. NDT and E Int 43(7):629–634
20. Birgisson B, Roque R, Page G (2003) Ultrasonic pulse wave velocity test for monitoring changes in hot-mix asphalt mixture integrity from exposure to moisture. Transp Res Rec J Transp Res Board 1832:173–181
21. Arabani M, Kheiry PT, Ferdosi B (2009) Laboratory evaluation of the effect of HMA Mixt parameters on ultrasonic pulse wave velocities. Road Mater Pavement Des 10(1):223–232. https://doi.org/10.1080/14680629.2009.9690189

22. Arepalli UM (2017) A study of moisture induced material loss of hot mix asphalt (HMA). Doctoral dissertation, Worcester Polytechnic Institute, Worcester
23. ASTM C597 (2016) Standard test method for pulse velocity through concrete. American Society for Testing and Materials
24. ASTM C125 (2016) Standard terminology relating to concrete and concrete aggregates. American Society for Testing and Materials
25. Nazarian S, Yuan D, Tandon V, Arellano M (2002) Quality management of flexible pavement layers with seismic methods. The Center for Transportation Infrastructure Systems, The University of Texas at El Paso., Texas