On the Combined Effect of Moisture Diffusion and Cyclic Pore Pressure Generation in Asphalt Concrete

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ABSTRACT

In this paper, a new moisture conditioning protocol which attempts to distinguish the contributions of long- and short-term moisture damage, i.e. moisture diffusion and cyclic pore pressure generation, in asphalt mixtures is presented. The capability of the proposed protocol to rank various asphalt mixtures of known field performance for their short- and long-term sensitivity to moisture is evaluated on the basis of the Tensile Strength Ratio. Asphalt specimens with different types of aggregates and asphalt binders were conditioned by various combinations of water bath immersion and cyclic pore pressures by means of the Moisture Induced Sensitivity Tester. The results show that the proposed conditioning protocol can be used to evaluate the moisture susceptibility of asphalt mixtures and distinguish among mixtures with different moisture damage characteristics. In addition, it is shown that the use of cyclic pore pressures has a significant effect and can be used as an accelerated moisture conditioning procedure.

INTRODUCTION

During their service life, asphalt pavements undergo a combination of traffic and environmental loadings that deteriorate their overall performance and eventually result in various forms of damage such as rutting, ravelling and cracking. Moisture damage has been identified as a major contributor to accelerated deterioration in asphalt pavements. At the material level, moisture induced damage can be expressed via two mechanisms: adhesion and cohesion. Depending on the traffic loading characteristics and climate conditions, the asphalt mixture type, as well as the type of asphalt binder and the quality of the aggregate-binder bond, failure due to moisture damage can be either of cohesive or adhesive nature *(1-4)*. Moisture diffusion, asphalt binder erosion due to fast water flows and pore pressure development from entrapped water in the air voids (i.e. pumping action) were identified as the physical and/or mechanical processes that ultimately can lead to pavement distresses *(5-6)*.

Moisture diffusion through asphaltic materials is a long-term process that affects the durability of asphalt concrete (AC) pavements (Figure 1). Each type of asphalt binder has its own diffusion characteristics described by the moisture diffusion coefficient D. As moisture infiltrates into the asphalt mixture, the physico-chemical properties of the asphalt binder can change *(7)* hence reducing its cohesive strength. Additionally, in the presence of moisture, the adhesive bond between aggregate and asphalt binder deteriorates and can eventually result to stripping *(2,3)*.

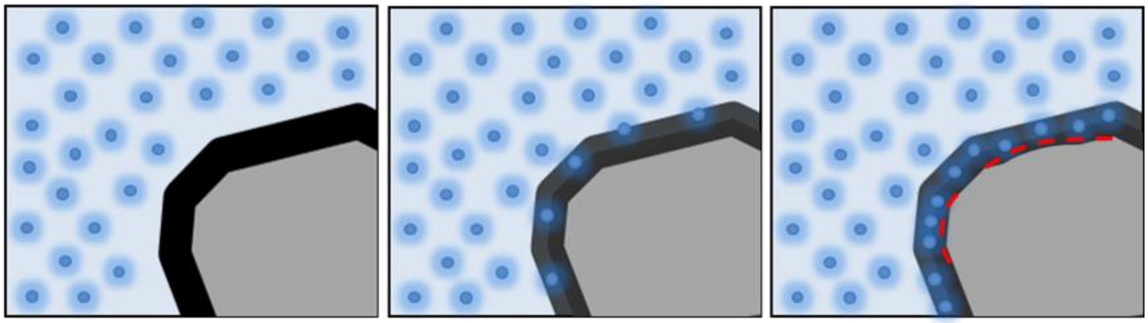

FIGURE 1 Damage of the binder and the binder-aggregate interface due to moisture diffusion.

A short-term damage mechanism, that can act accumulatively, and/or accelerate the aforementioned damage mechanisms, is pumping action *(2, 6, 8)*. In asphalt mixtures some of the pores are interconnected and allow the water to move through the pavement. Dynamic traffic loads can cause high water pressure fields within the pores that are filled with water. These high pore pressures can lead to cracking of the binder film thus facilitating the ingression of moisture to the asphalt binder-aggregate interface (Figure 2). Additionally, the intense pore pressures can cause desorption of the weakened binder, referred to as “erosion” *(2)*.

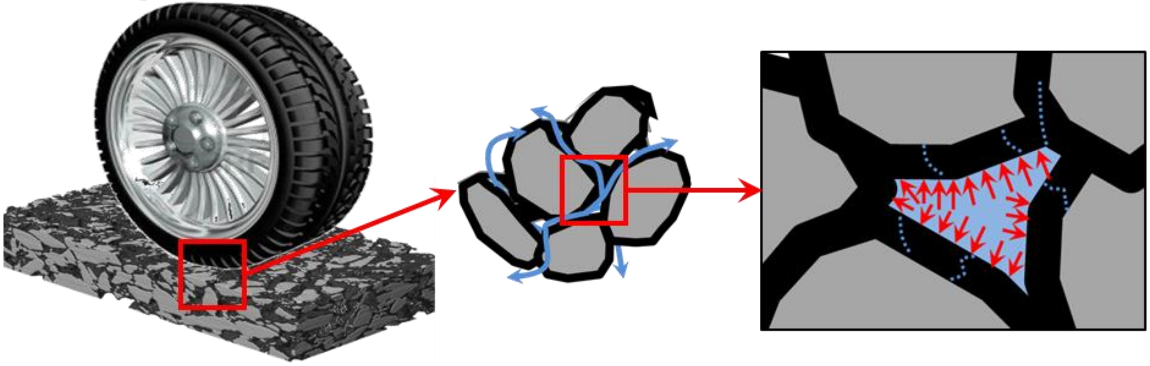

FIGURE 2 Pore pressure development due to pumping action.

Several test procedures have been proposed in the past for the evaluation of moisture susceptibility of asphalt concrete mixtures including the Boiling Water Test (ASTM D3625), Static Immersion Test (AASHTO T-182), Tunnicliff and Root Conditioning (NCHRP 274) and the modified Lottman (AASHTO T283) *(9)*. The modified Lottman test is commonly used for identifying the moisture damage potential. In spite of its acceptance, the moisture conditioning protocol described in this test fails to capture the time frame over which moisture infiltration occurs and furthermore disregards the short term moisture processes related to pumping action *(10)*. In addition, field observations have shown that stripping of open asphalt mixes is a rather localized phenomenon in trafficked areas of a pavement which are oversaturated with water *(11)*. These findings strengthen the claim that pumping action can be an important damage mechanism which acts concurrently with the long term damage processes and contributes to premature failure in asphalt pavements.

In the first part of this contribution, a new moisture conditioning protocol is presented which attempts to distinguish the contributions of short- and long-term moisture damage to mix degradation. In the second part, the capability of the protocol to rank various asphalt mixtures of known field performance for their short- and long-term sensitivity to moisture is evaluated on the basis of the Tensile Strength Ratio.

MATERIALS

In this study, six asphalt mixture compositions, commonly used in the Netherlands for open graded asphalt concrete pavements, were tested. The mixtures differed in terms of the type of aggregates and bitumen used. For a better control of the test variables, a similar gradation, Table 1, with a nominal maximum aggregate size of 16 mm was used. The specimens were produced using either granite (known to be prone to moisture damage) or sandstone (with known good field moisture damage performance) aggregates.

TABLE 1 Aggregate Gradation of Porous Asphalt Mixtures

Sieve size (mm)	22.4	16	11.2	8	5.6	2
Percentage passing (%)	100	97.99	73.32	23.38	8.15	0.83

In addition, three different bitumen types were used: a conventional bitumen Pen 70/100, a moderately polymer modified bitumen with 50/80 pen grade and a highly polymer modified one with 65/105 pen grade. A target bitumen content of 4.5% by total mixture mass was selected for all the specimens. Hydrated lime filler (Wigro 60K) was added at 4.8% by mass of total aggregate. The different mixtures are denoted as: GP, GM, GH, SP, SM, SH, with the letters G and S denoting Granite and Sandstone aggregates respectively, while the letters P, M and H denote the bitumen types used (Pen 70/100, moderately modified and highly modified bitumen).

Cylindrical samples, 150 mm in diameter and 150 mm in height, were produced using the Superpave Gyratory Compactor (SGC). Then a 101.6 mm diameter samples were cored from the centre of the gyratory specimens. The samples were further sliced into 50 mm thick specimens in order to be used in the MIST and the Indirect Tensile Test (ITT).

SHORT- AND LONG-TERM MOISTURE DAMAGE SUSCEPTIBILITY PROTOCOL

Moisture diffusion and pumping action were identified as the dominant moisture damage inducing mechanisms. However, the time frame over which each mechanism occurs in the field differs significantly. Moisture infiltration occurs over a longer timeframe, while excess pore pressure development takes place in very short times. In order to address the individual damage mechanisms associated with these two damage inducing processes, a new test protocol is presented in the following which consists of the combination of two different conditioning methods: (a) bath conditioning and (b) cyclic water pore pressure application.

Bath conditioning is performed at elevated temperatures so as to facilitate the infiltration of water into the asphaltic mixture and, consequently, to accelerate the long-term degradation of the material properties. To decide on the duration of the moisture conditioning phase in the water bath, a series of Finite Element (FE) simulations of moisture diffusion into cylindrical asphalt concrete specimens were performed.

Cyclic pore pressure generation in the asphalt mixture is achieved by means of the Moisture Induced Sensitivity Tester (MIST). The MIST was designed as an accelerated conditioning device for the evaluation of the resistance of an asphalt mixture to stripping by simulating the high pressure fields which develop within an asphalt layer due to traffic loading *(12)*.

MIST is a self-contained unit, Figure 3(a), which includes a hydraulic pump and a piston mechanism that is designed to cyclically apply pressure inside a sample chamber. The test involves placing a 100 mm or 150 mm diameter sample of 25 to 150 mm height inside the sample chamber, Figure 3(c), filling the chamber with water, closing the sample chamber lid, choosing the preferred conditioning settings and starting the test. Then, the machine automatically heats the sample to the desired temperature and starts cycling between zero and the selected pressure. Tests can be performed at different pressures and temperatures to replicate different traffic and environmental conditions. Furthermore, the user can specify the desired number of conditioning cycles.

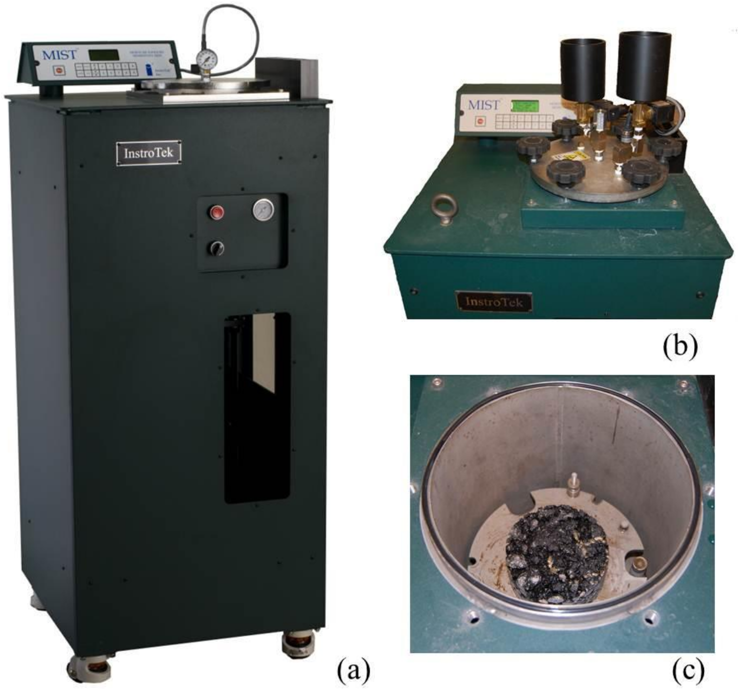

FIGURE 3 Moisture induced sensitivity tester.

In this contribution, cylindrical samples of 101.6 mm diameter are utilised. The specimens are first subjected to moisture infiltration by placing them in a bath filled with distilled water, at a temperature of 60 °C. At fixed time intervals of 2, 4, 6 and 8 weeks, three specimens per mixture are removed from the bath, placed in a bath at 20 °C for 2 hours and then stored at a climatic chamber at 20 °C until tested for their strength using the ITT. The rest of the samples are further conditioned in the MIST device by applying 3500 cycles of water pumping action at a temperature of 60 °C and a pressure of 70 psi (0.48 MPa). After MIST conditioning, the samples are placed into a water bath at 20 °C and kept there for 2 hours before ITT testing, Figure 4.

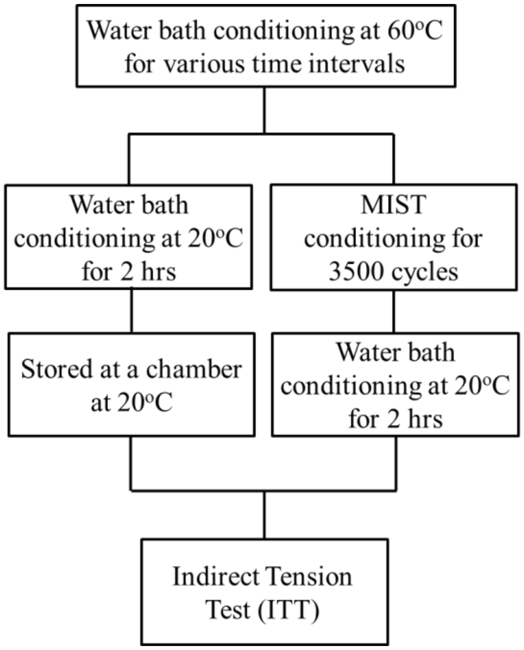

FIGURE 4 Schematic of the applied moisture conditioning protocols.

In the proposed protocol, the assessment of AC mixtures for their moisture damage susceptibility was performed via the Indirect Tensile Strength (ITS) and the Tensile Strength Ratio (TSR). The variability of the TSR parameter and the associated ITT test, in combination with its poor relation to field performance cast doubt on the effectiveness of TSR in determining the potential of AC mixtures for moisture damage *(10, 13)*. However, since the objective of this contribution was to evaluate the proposed conditioning protocol for its ability to distinguish among mixtures with different moisture damage characteristics, the TSR parameter is utilized in this contribution so as to facilitate comparison with previous studies.

Determination of Moisture Conditioning Time

In order to ensure a homogenized moisture concentration profile in the AC specimens and avoid variations in the ITT results, parametric FE simulations of moisture diffusion into an AC specimen were performed by means of the CAPA-3D FE system developed at Delft University of Technology *(14)*. From the results, the time required for moisture infiltration into the asphalt specimen was estimated and a decision on the duration of the moisture conditioning phase for the suggested protocol was made.

Moisture diffusion through the asphalt mixture components is considered to be a process that occurs at molecular level. In the CAPA-3D FE system, moisture diffusion is assumed to follow Fick's second law

$$\frac{\partial \theta}{\partial t} = \nabla \left(D \nabla \theta \right) \tag{1}$$

where $0 \leq \theta \leq 1$ is the normalized moisture concentration in the material at any given time and D is the moisture diffusion coefficient which is the controlling parameter of the diffusion process, it is an intrinsic material property and can be determined experimentally. In this contribution, the coefficient of diffusion is treated as a constant. The normalized moisture concentration is defined as the ratio of the concentration at any given time over the maximum moisture concentration according to the equation

$$\theta = \frac{C_t}{C_{\max}} \tag{2}$$

The analyses were performed on 3D micromechanical meshes obtained from real AC cylindrical specimens. X-Ray Computed Tomography (CT) was utilised as a non-destructive technique in order to obtain the digital description of the internal structure of the asphalt specimens. Then, Simpleware *(15)* software was used to enable the conversion of the CT scan images into FE meshes.

Each component of the asphalt mixture i.e. aggregates, mastic (asphalt binder plus fines) and air voids, has its own moisture diffusion coefficient *D*. Based on the work of Kringos et al. *(16)*, the diffusion coefficients for the mastic and the aggregates were specified as 11.08×10^{-3} and 0.72 mm^2/hr, respectively. The diffusion coefficient of the air void phase was assumed as 0.26 mm^2/hr, a value reported in the study of Kassem et al. *(17)*. During the simulations, a constant moisture boundary condition was applied on the surface of the asphalt specimen.

For the presentation of the results, a number of nodes were selected as output locations for the moisture concentration values. All the selected nodes are lying on the diameter of the specimen and are located 1 mm above the bottom surface of the sample as shown in Figure 5(a).

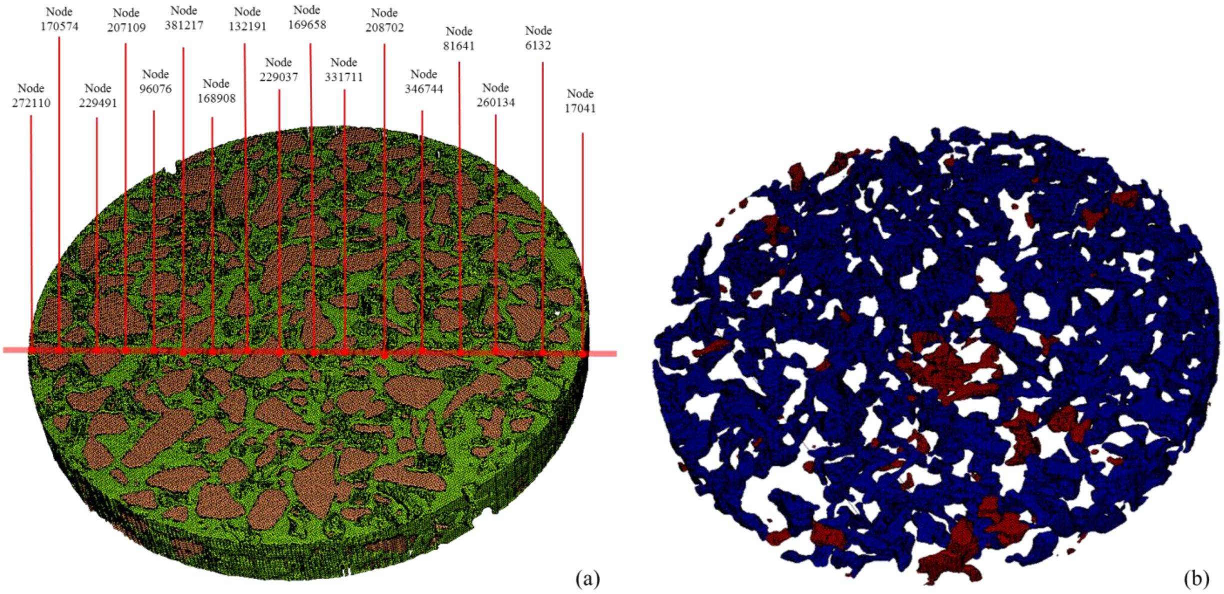

FIGURE 5 (a) Output locations for normalized moisture concentration and (b) air void phase of the AC specimen.

The normalized moisture concentration profile, along the diameter of an asphalt specimen, at different time intervals is shown in Figure 6. It can be observed that the moisture profile is non-uniform along the diameter of the AC specimen and that different parts of the specimen require different time intervals to reach full saturation.

The generated moisture profile can be justified if the distribution of air voids and their interconnectivity in the body of the specimen are taken into account. In Figure 5(b), the air void distribution of the specimen is illustrated. In blue color the interconnected voids are shown, whereas the inaccessible air voids are in red color. It can be observed that the peak shown in the graph, Figure 6, coincides spatially with the presence of isolated voids in the specimen. This discontinuity in the air void network is a hindrance to the diffusion of moisture in that specific location of the sample.

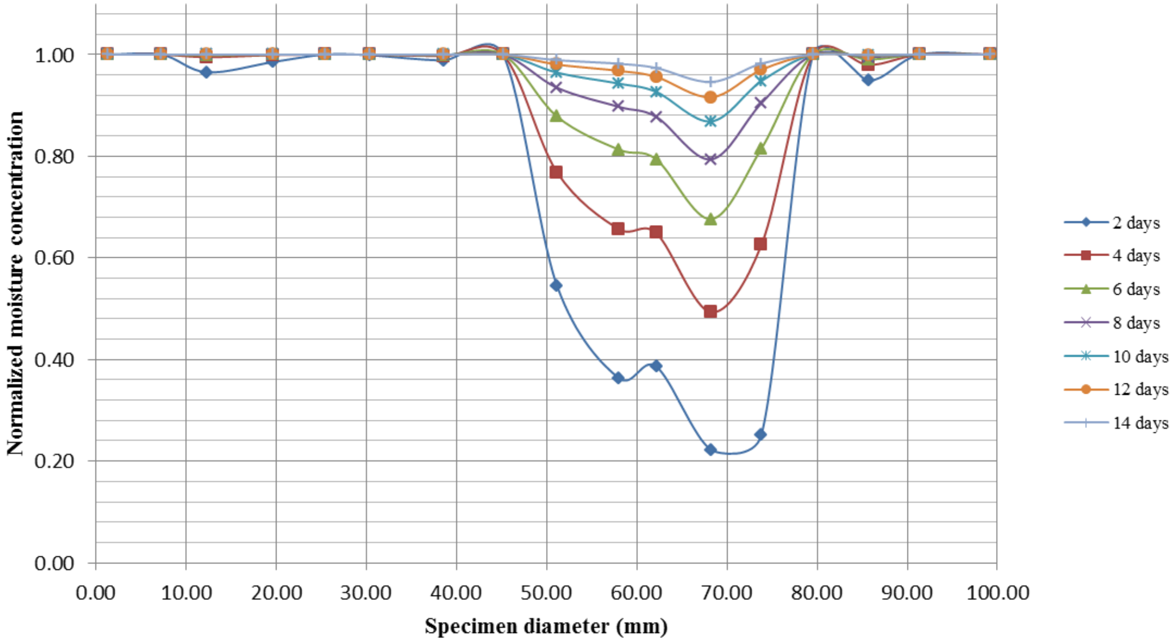

FIGURE 6 Normalized moisture concentration profile along the diameter of the specimen at different time intervals.

From the results of the FE simulation it is clear that, after 14 days of diffusion, moisture concentration within the body of the specimen reached its maximum value and the specimen can be considered fully saturated. Therefore, the first time interval of the moisture conditioning phase of the combined protocol was chosen to last for 2 weeks. This amount of time was selected so as to ensure a spatially homogenized moisture profile in the asphalt specimens.

Determination of MIST Conditioning Cycles

In setting up the new moisture conditioning protocol, the optimum number of MIST conditioning cycles was determined on the basis of MIST tests on an AC mixture with sandstone aggregates and polymer modified binder. AC specimens were placed into the MIST without any prior conditioning.

The goal was to induce enough damage so as to distinguish among mixtures with different moisture damage susceptibility. Three sets of specimens were utilised in replicas of three. 1000 cycles were applied on the specimens of the first set, 4000 on the specimens of the second and 8000 on the third set. The experimental mean ITS values are plotted in Figure 7.

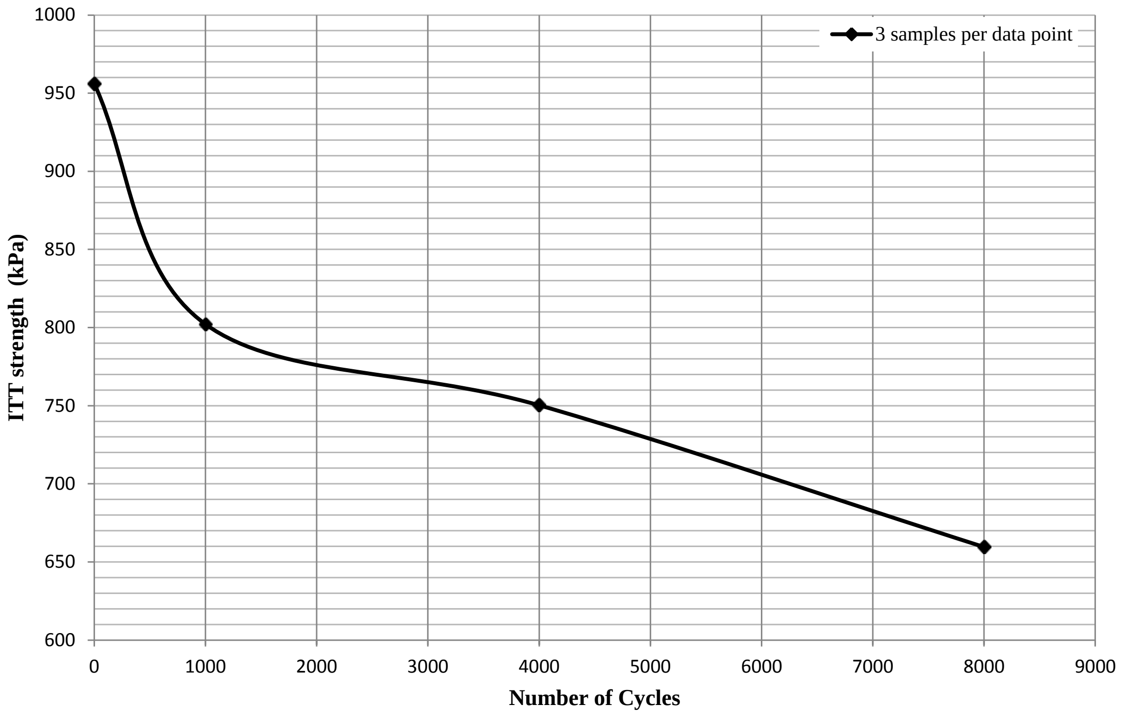

FIGURE 7 Impact of the number of MIST cycles on the indirect tensile strength.

As expected, the increasing number of cycles led to more damage at the same temperature and pressure (60 ^{o}C and 0.48 MPa were used respectively). It was observed that at 4000 cycles, the specimens showed a reduction in strength of about 25% which was considered sufficient for the evaluation and ranking of asphalt mixtures. For other types of mixes the recommended number of cycles may vary.

TEST RESULTS AND DISCUSSION

The evaluation of the proposed protocol for its ability to discriminate amongst mixtures in terms of moisture sensitivity was attained via the Tensile Strength Ratio (TSR). The mean TSR values (out of 3 replicas) after each conditioning period are shown in Figure 8. Also, the coefficient of variation for every mix, at each conditioning level, was calculated and is presented on the top of the bars.

It is observed that the TSR values decrease over conditioning time for all asphalt mixtures, which is in accordance with the expectations. The solid red line represents the threshold value below which an asphalt mixture is considered to be more susceptible to moisture damage, according to the Dutch standards *(18)*.

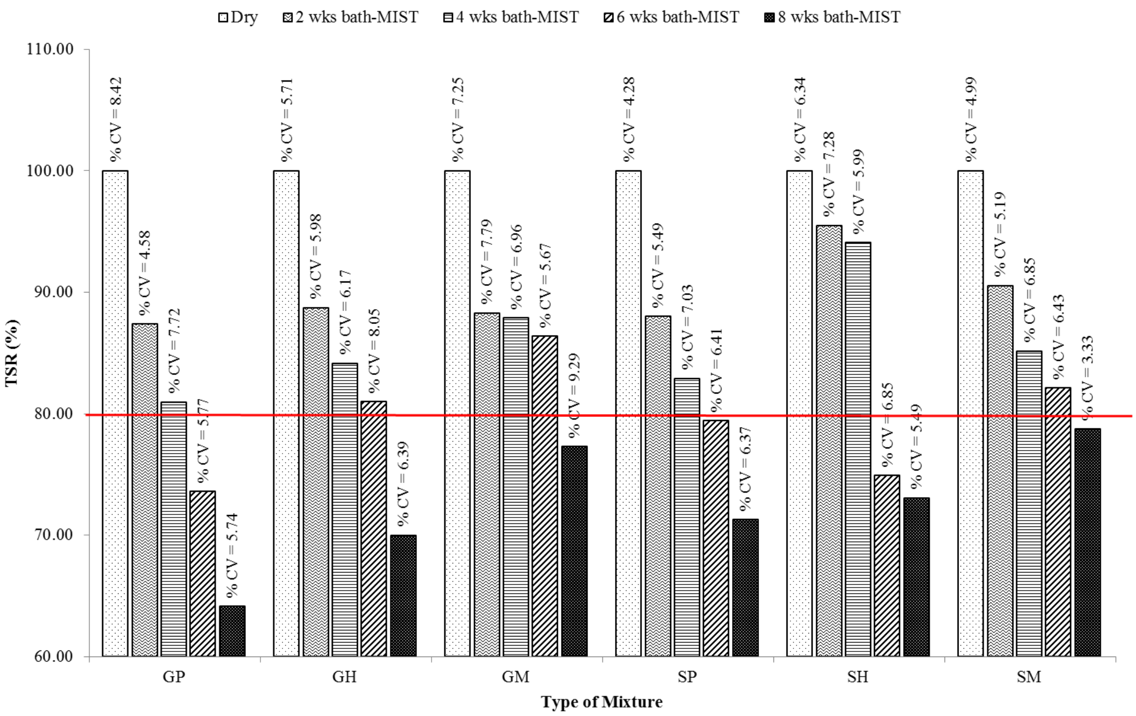

FIGURE 8 Mean TSR values after the application of the combined protocol for various conditioning times.

Evaluation of the Combined Moisture Conditioning Protocol

In Figures 9 and 10, the influence of the combined moisture conditioning protocol (hereafter called combined protocol) and the effect of moisture diffusion due to bath conditioning alone (hereafter diffusion protocol) on the ITS of the specimens are plotted. From the results, the contributions of the short- and long-term moisture damage on the strength of the specimens can be quantified.

Specifically, after applying the combined protocol for 8 weeks, the tensile strength (in comparison to the ITS of the dry unconditioned specimens) reduced by 28.7%, 26.9% and 21.3%, while for the diffusion protocol the decrease was 11.6%, 20.2% and 9.3% for the SP, SH and SM mixtures, respectively.

Similarly, for the GP, GH and GM mixtures the combined protocol gave a reduction of 35.8%, 30% and 22.7%, whereas the diffusion protocol lead to a decrease of 24.3%, 20% and 9%, respectively. The results showed that after the application of both protocols, the tensile strength of the specimens decreased over conditioning time, as expected. Also, it can be seen that the proposed combined protocol has a stronger effect on the ITS compared to the diffusion protocol.

The difference between the curves of the two applied protocols corresponds to the contribution of the cyclic pore pressures to the total damage of the specimens. Additionally, it can be observed that the distance between the two curves increases with bath conditioning time for four out of the six mixtures. This can be explained by the fact that both damage mechanisms: moisture diffusion and high pore pressure development are present in the combined protocol. As the duration of the long-term moisture conditioning increases, the properties of the mixture components degrade further. Hence, the same amount of MIST conditioning has a greater influence on the strength of the specimen.

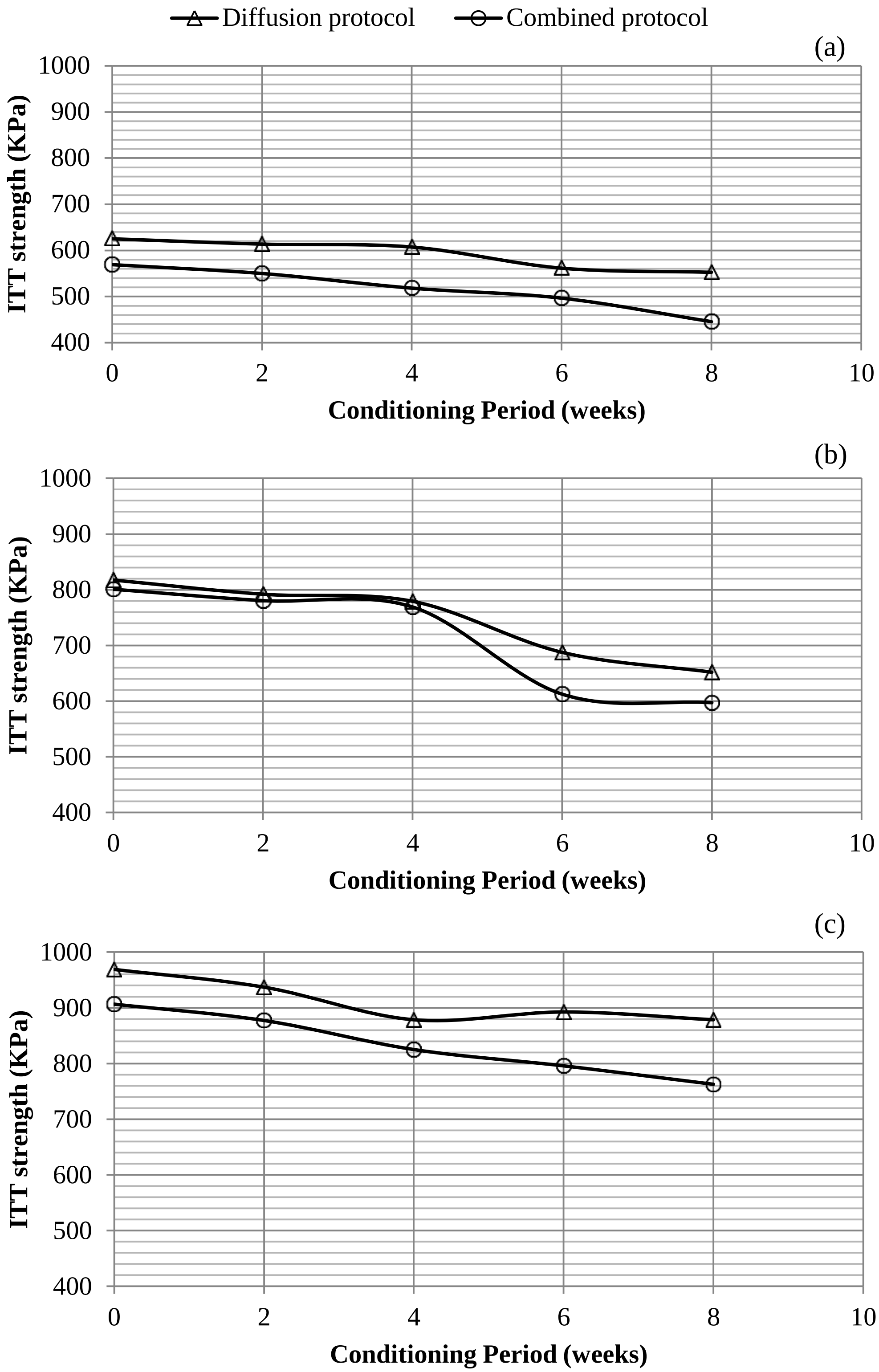

FIGURE 9 Impact of the applied moisture conditioning protocols on the indirect tensile strength of the (a) SP, (b) SH and (c) SM asphalt mixtures.

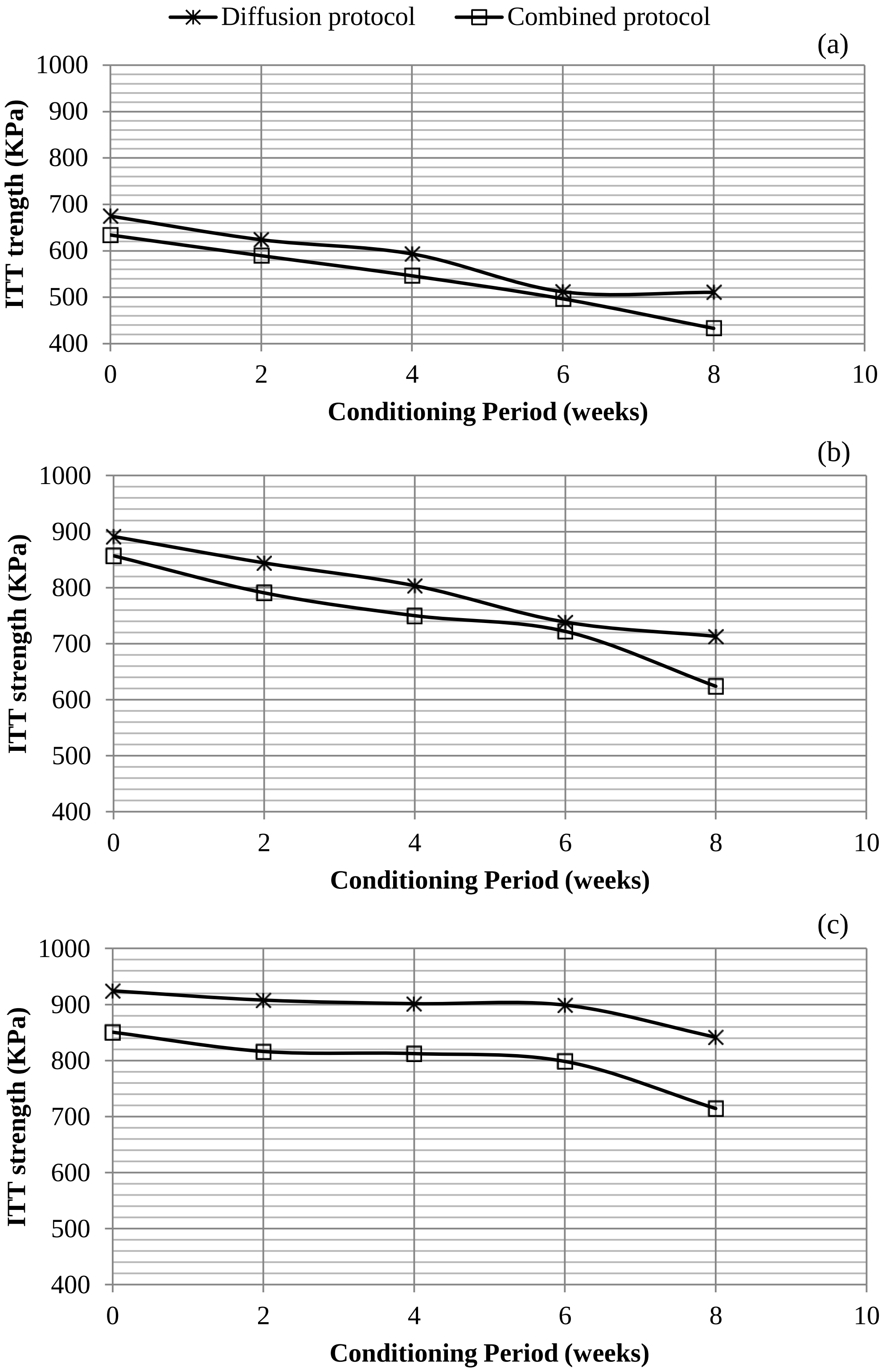

FIGURE 10 Impact of the applied moisture conditioning protocols on the indirect tensile strength of the (a) GP, (b) GH and (c) GM asphalt mixtures.

Influence of Aggregate and Binder Type

The effect of the aggregate type was investigated by replacing the granite aggregate with a sandstone one, whilst keeping the same binder type for the various mixtures. As shown in Table 2, for all three binders, the sandstone aggregate mixtures have demonstrated better moisture damage performance than those containing granite aggregates. In an earlier study by Kringos et al. *(16)*, in which the same materials were used, field observations showed that sandstone aggregates have better moisture performance than granite ones and this is in agreement with the findings of this research.

TABLE 2 Mean ITS Values for the Various Mixtures

Duration of combined conditioning protocol (weeks)	Mean Indirect Tensile Strength (kPa)					
	Type of mixture					
	SP	SH	SM	GP	GH	GM
0	569.14	800.87	906.55	634.07	856.89	850.52
2	550.04	780.50	877.26	589.51	790.68	816.15
4	518.21	769.04	825.06	546.22	749.94	812.33
6	496.56	612.43	795.77	496.56	721.93	798.32
8	445.63	597.15	762.67	432.90	623.89	714.29

Also, in previous studies *(16, 19)*, the effect of polymer modification on moisture susceptibility has been investigated. It has been reported that polymer modified binders are less susceptible to moisture damage compared to the non-modified. In this study, by comparing the mixtures in terms of the type of binder used, it is shown that the use of polymer modified bitumen increases the resistance of the mixture to moisture damage. Moreover, it is observed that moisture sensitivity increased when binders prepared with softer bitumen are used. The same observations are reported in a study by Grenfell et al. *(20)*.

CONCLUSIONS

In this paper, a new moisture conditioning protocol was developed which is capable of distinguishing between the short- and long-term processes that induce moisture damage to AC mixtures. A laboratory study was conducted to evaluate the ability of the new conditioning protocol to determine the resistance to moisture damage of a range of asphalt mixtures.

From this research, it can be concluded that the conditioning procedure developed can be used to evaluate the moisture susceptibility of asphalt mixtures and distinguish among mixtures with different moisture damage potential. Furthermore, the developed protocol enables the quantitative determination of the individual short- and long-term contribution to the overall specimen damage. In addition, it is shown that the use of cyclic pore pressures has a significant effect and can be used as an accelerated moisture conditioning procedure. Because the protocol was decided on the basis of porous asphalt mixtures, further research is needed to determine the conditions for testing mixtures with lower air void content.

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