Asphalt mixture performance and testing

EVALUATION OF PERFORMANCE PROPERTIES OF ASPHALT MIXTURES USING NANO-ORGANOSILANE ADDITIVE

Yalcin Karakaya, Ayhan Oner Yucel, Murat Guler
Department of Civil Engineering, Middle East Technical University, Ankara, Turkey

Abstract

In this study, the performance of zycotherm- a liquid, nano-organosilane anti stripping additive- on the tensile strength and rutting resistance of asphalt concrete was investigated. To carry out the study, a detailed experimental program was scheduled including, indirect tensile strength test and Hamburg wheel-track test, to evaluate the tensile strength and rutting resistance of the mixtures respectively. The mixture designs were performed using the standard Marshall mixture design methodology for two types of aggregate and with/without chemical additive. Optimum bitumen contents for four different mixture types were determined for the design air void of 4%. The test results showed that, the use of anti-stripping additive, increased the IDT strength of the mixtures by up to 24.7%. In terms of rutting performance, the specimens having nano-organosilane additive, yielded smaller rutting than their control mixtures up to 11.6%.

This paper was first published in 2020 in version 1.0 of the proceedings of the 7th E&E Congress. This second edition (version 1.1.) of the proceedings is published in June 2021. The content of this paper has not changed, but the author(s) may have provided additional information in the form of an annex.

1. INTRODUCTION

Asphalt is a viscoelastic material that experience elastic behaviour under rapid loading or at low temperatures and viscous behaviour under slow loading or at high temperatures. This temperature-dependant nature of asphalt causes rutting that usually appears at high temperatures and cracking that mostly happens at low temperatures. Furthermore, temperature variations and increased traffic loads, create critical pressures within the pavement structure and promote these types of distresses. Such problems led to an increased desire to improve the asphalt properties. Asphalt modification has been one of the most common methods in this regard.

Among the various methods to modify the asphalt properties, application of nanotechnology has rapidly become widespread. Especially, the use of nano-organosilane in the field of asphalt modification has been gradually increasing. Most of the reported studies confirmed the positive effect of zycotherm, a silane-based nano-additive, in terms of moisture susceptibility of asphalt [1-9]. The silane-based additive creates a hydrophobic nanolayer on aggregates and eliminates water-sensitive surface permanently, makes the surface oil-loving [2]. Although, the moisture damage can be reduced by both the silane-based new technology additive and the typical anti-stripping agents (amines), the main difference between zycotherm and amines is that zycotherm eliminates water-sensitive surface permanently and turns it to oil-loving, whereas amines do not chemically modify the surface. Instead, it always remains hydrophilic and thus leads to moisture susceptibility [2].

In addition to its well-known improvement on moisture sensitivity, the effect of zycotherm on the performance properties of asphalt have been also studied. The effect of nanotechnology zycosoil as an anti-stripping agent on the moisture sensitivity and some mechanical properties of glasphalt mixtures were evaluated by Behbahani et. al. [10]. The modified mixtures showed higher mechanical properties than those of conventional ones and it was concluded that the improvement of bitumen stiffness because of using zycosoil was the main reason for the increment of the stiffness modulus and reduction in permanent deformation of glashpalt samples [10]. Ibrahim and Mehan [11], investigated the effects of nanomaterial in terms of moisture induced damage, rutting, fatigue and low temperature cracking. The results of dynamic shear rheometer tests (DSR) and bending beam rheometer tests (BBR) showed that using silane-based additive greatly increases the resistance of asphalt to moisture induced damages and also increases its resistance to rutting, fatigue and low temperature cracking [11]. In their study, the permanent deformation of pure and nano-organosilane-modified bitumen were evaluated by Mirzababaei et. al. [12]. Based on $G^*/\sin\delta$ values of dynamic shear rheometer tests and nonrecoverable compliance (Jnr) values from multistress creep recovery tests, the modification of bitumen improves the rutting performance [12]. The resistance of asphalt against moisture damage and fatigue cracking was also proven to be improved by using zycotherm as an anti-stripping agent [13]. Additionally, other studies in literature confirmed the effectiveness of nano-organosilane additive on the mechanical properties of asphalt [14-17].

The objective of this study was to investigate the effect of zycotherm has on the tensile strength and rutting resistance of asphalt mixtures. A detailed experimental program including, indirect tensile strength test and Hamburg-wheel track test was planned. The samples were prepared according to Marshall mixture design method with two different types of aggregate, i.e., low and high absorptive. The study program mainly focused on testing the improved bitumen-aggregate bonding by the nano-organosilane additive, so that the tests were repeated at extended conditioning times to compare the results with the normal (standard) testing conditions.

2. MATERIALS AND METHOD

2.1. Aggregate

Two types of basalt aggregates were used while preparing the specimens. Type 1 aggregate is a highly porous aggregate with an absorption of around 2.7% and known by its stripping problem. Type 2 aggregate on the other hand, a low porosity aggregate with and absorption of 1.8% and rated as a good aggregate for wearing courses by the local contractors. Apart from their absorption rates and LA abrasions, the two aggregates are quite similar in terms of physical properties. The measured aggregate properties and the regarding testing standards are given in Table 1. The aggregate gradation was selected based on the local authority, Turkish General Directorate of Highways (TGDH), gradation requirements for wearing courses. As it can be seen from the Figure 1, the design gradations for both aggregates selected are quite similar, apart from a minor deviation with the sieve No. 3/8, so that the effect of gradation will not be a major factor on the test results when evaluating the performance of the additive.

Table 1. Measured aggregate properties

Properties	Type 1	Type 2	Test Standard
LA abrasion loss (%)	16	23	TS EN 1072-2
Flatness index (%)	13.6	17.3	TS EN 933-3
Bulk specific gravity (coarse aggregate)	2.669	2.706	TS EN 1097-6
Bulk specific gravity (fine aggregate)	2.621	2.760	TS EN 1097-6
Apparent specific gravity (filler)	2.856	2.842	TS EN 1097-6
Coarse aggregate absorption (%)	2.4	1.8	TS EN 1097-6
Fine aggregate absorption (%)	3.0	1.8	TS EN 1097-6

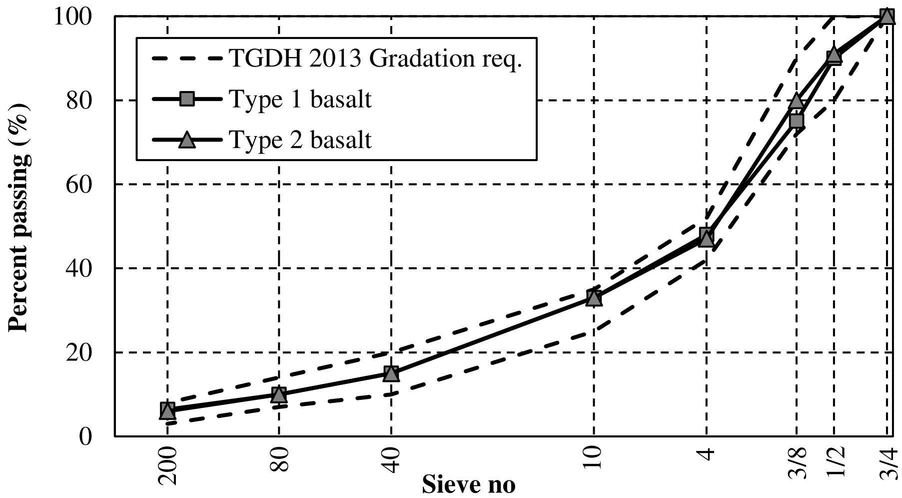


Figure 1. Gradation of aggregates in accordance with TGDH specifications

2.2. Bitumen and additive

In the experiments, penetration grade PG 50/70 bitumen was provided by the Turkish General Directorate of Highways (TGDH). The properties of the bitumen are presented in the Table 2. Zycotherm is a silane-based nanotechnology additive to bitumen, to be added before bitumen is mixed with aggregates. Physical properties of the additive are presented in the Table 3. The manufacturer guidelines state that the mixing procedure should be at 150 ºC by a mixer that can create a vortex with a depth of 2-3 cm. In order to provide a homogeneous distribution, nanomaterial must be added to bitumen in drops using a syringe over a span of 10 min. The silane-based additive consists of both organic and inorganic parts and establishes covalent bonding to bitumen and aggregate. While mixing the additive and binder at high temperatures, the inorganic part solves and the hydrogen bonds break, leading to production of H_2O molecules. The inorganic part of the anti-stripping agent than establishes Si-O-Si covalent links with presence of H_2O molecules and thus a hydrophobic layer that prevents penetration of moisture into the aggregate-bitumen interface is created [6].

Table 2. Bitumen properties

Properties	Bitumen
Penetration (0.1 mm)	54
Specific gravity (g/cm^3)	1.025
Viscosity (cP at 135 ºC)	361
Ductility (cm)	>100
Softening Point (ºC)	52

Table 3. Properties of the additive

Properties	Bitumen
Specific gravity (g/cm^3)	1.04
Physical state	Liquid
Colour	Pale yellow
Viscosity (cP at 25 ºC)	100-500
Flash point (ºC)	90

2.3. Mixture design method

The Marshall mixture design method was used while preparing the specimens. Since zycotherm affects the wetting characteristics of bitumen, separate designs were conducted for the same aggregate sources while modification of the bitumen; hence two designs for type 1 aggregate (with/without additive) and two designs for type 2 aggregate (again with/without additive) were conducted. The trial samples were compacted using 75 blow counts. The optimum bitumen contents were calculated with the 4% of design air void. Additionally, the stability and the flow values, voids in mineral aggregate (VMA), and voids filled with asphalt (VFA) were checked.

The results of Marshall mix design are shown in Table 4. Type 1 basalt aggregate, due to its high absorptivity, resulted in slightly higher optimum bitumen content (5.72%) when modified, as compared to its control mixture, which is 5.55%. This is a direct result of the fact that zycotherm improves the wetting characteristics of bitumen and helps to increase the amount of absorbed bitumen inside the aggregate. It is also worth mentioning that, the stability of the samples with the type 1 aggregate are slightly lower when modified, hence yielding higher flow values although the specification requirements are satisfied. The silane-based additive however, showed different results on the design values of the samples with type 2 aggregate. Although, the optimum bitumen contents were not changed, the stability values were increased significantly in spite of the increase in the flow values. This can be perhaps explained by the improved bonding between bitumen and aggregate that was provided by the zycotherm, leading increased stability of the mixtures.

Table 4. Marshall mix design results

Properties	Type 1 aggregate		Type 2 aggregate		TGDH req.
	Without additive	With additive	Without additive	With additive	
Optimum bitumen ratio (%)	5.55	5.72	5.70	5.70	4-7
Bulk specific gravity(g/cm^3)	2.409	2.409	2.475	2.479	-
Air void (%)	4.03	4.03	4.09	4.05	3-5
VMA (%)	14.2	14.3	14.4	14.3	≥14
VFA (%)	71.6	71.9	71.6	71.6	65-75
Stability (kg)	1490	1220	1380	1745	≥900
Flow (mm)	2.50	4.00	2.87	3.21	2-4
Filler / Bitumen ratio	1.15	1.12	1.05	1.05	-

3. LABORATORY TESTING PROGRAM

3.1. Indirect tensile strength test

In the experiments, most of the study effort was given into the indirect tensile strength testing of asphalt to evaluate how effectively zycotherm improves the bitumen-aggregate bonding. The adopted test method, AASHTO T283, is the most frequently used test for measuring the moisture-induced damages of asphalt [10].

In the tests, 4 combinations were generated with three replicates, i.e., two types of aggregate and with/without modification. First the specimens were compacted by Marshall hammer to obtain 7 ± 0.5 percent of air void. Then, they separated into two groups, a control group without moisture conditioning and another group that are saturated up to 50-88% in water solution. Another test parameter was also extended conditioning times up to 120, 168 and 336 hours with one freeze-thaw cycle. Hence, together with the 24 h standard conditioning time, a total of 20 test combinations were generated. Besides, each test was represented by three replicates, resulting in a total of 60 specimens. The indirect tensile strength (IDT) values for each sample were then calculated using the following formula [18]:

$$\mathbf{IDT} = \frac{\mathbf{2P}}{\boldsymbol{\pi}\mathbf{DT}} \tag{1}$$

where *IDT* is the tensile strength (in kPa). *P* is the peak load (in N), *D* is the diameter of the specimen (in mm). *T* is the specimen's thickness (in mm). Finally, tensile strength ratio (TSR), was calculated for each specimen by the ratio of conditioned IDT over unconditioned IDT. Minimum 80% of TSR is recommended for asphalt mixtures and higher TRS values indicate lower moisture susceptibility of specimens [8].

$$\mathbf{TSR} = \frac{\mathbf{IDT_{con}}}{\mathbf{IDT_{uncon}}} * \mathbf{100} \tag{2}$$

3.2. Hamburg wheel-track test

Wheel tracking test is a simulative test to predict measured rut depth [19]. The combined effect of rutting and moisture damage can be measured by rolling a 47 mm wide wheel across the rectangular specimens that are immersed in 50 °C water [20]. In this study, four different design combinations, i.e., type 1 aggregate, type 2 aggregate and with/without modification were tested according to the AASHTO T324. Specimens having 260 x 320 x 50 mm dimensions and around 6% air voids were used until either 30,000 cycles or 20 mm of rutting was obtained.

4. TEST RESULTS

4.1. IDT test results

The indirect tensile strength results for type 1 and type 2 aggregates are given in the Figure 2(a,b), separately. All the test specimens with organo-silane additive showed higher tensile strength values than those without it. For both types of aggregate, in spite of the reduce by extended conditioning times, zycotherm proved an improved IDT strength in general. The effect of conditioning time on the IDT strength results can be seen from the Figure 3(a,b). The plot on the left shows the IDT strength logarithm of the conditioning time relation for type 1 high absorptive aggregate and on the right the same relationship is plotted for the type 2 low absorptive aggregate. It can be easily seen that the use of zycotherm essentially offsets the strength-log-time relation of the normal mixtures and that both curves show nearly the same slope, i.e., rate of degradation in the IDT strength with the extended conditioning times.

From these plots, the corresponding conditioning times for a given strength value can be easily determined for with/without modification. For instance, at a strength value of 6.4 kg/cm^2, the corresponding conditioning time for normal mixtures is 24 hours while it seems around 72 hours with the modification. The similar result can be seen with the type 2 aggregates for 7.7 kg/cm^2 of strength value, the conditioning time for normal conditions is 120 hours while it will be around 480 hours when modification is used. Hence, the data indicates that to reach the same strength value for an asphalt sample with zycotherm, it must be conditioned nearly 3 times more than the sample without it. This factor of 3, in fact, represents the contribution of zycotherm to the IDT strength in the time scale. In comparison with the IDT results for two types of basalt aggregate, the low absorptive aggregate seems to yield higher IDT strength values at the same testing conditions and the duration of conditioning times due to its low absorptivity.

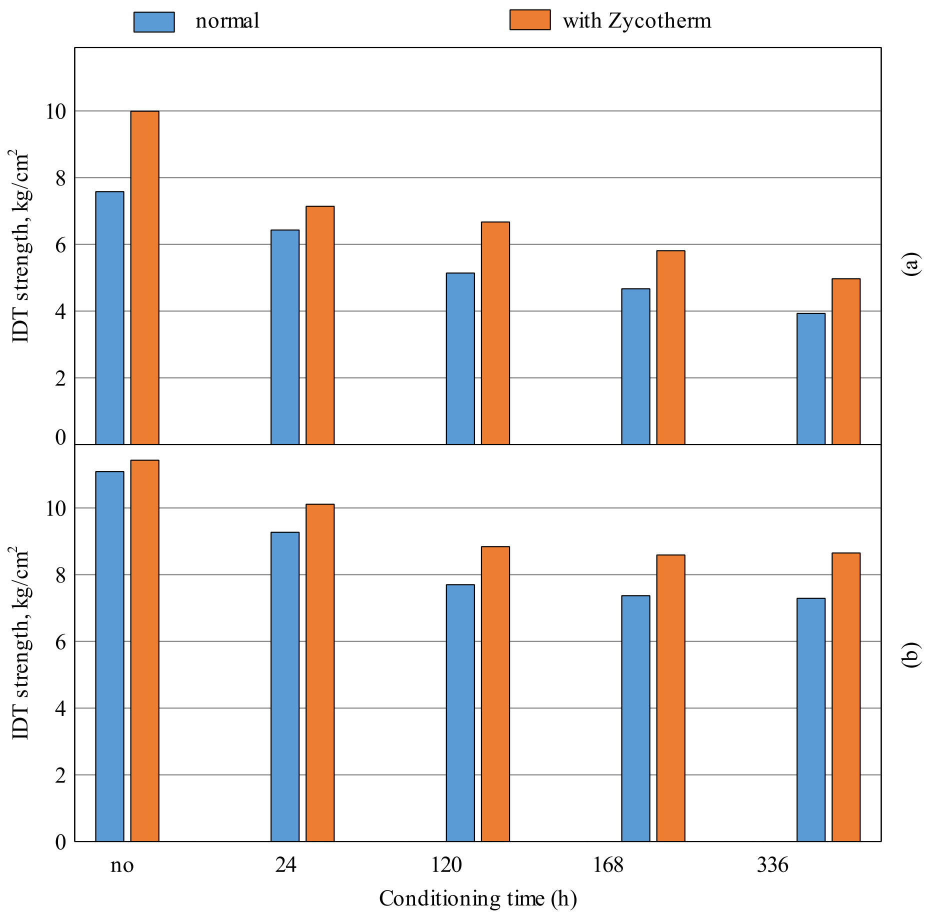
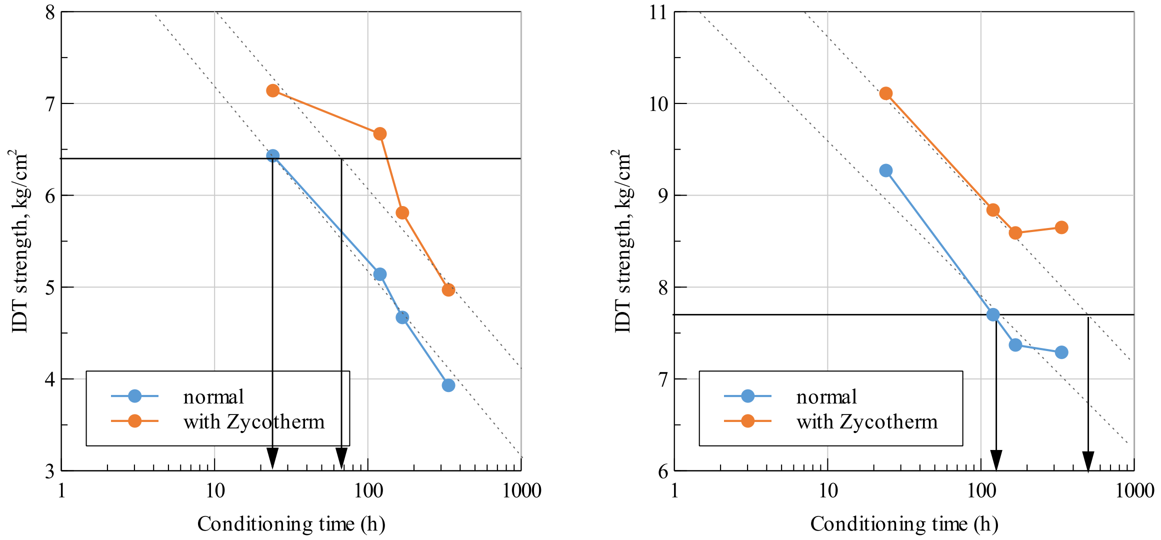


Figure 2. IDT test results: (a) high absorptive aggregate, (b) low absorptive aggregate



(a) (b)

Figure 3. IDT strength-conditioning time relation: (a) high absorptive aggregate, (b) low absorptive aggregate

Final comparison of IDT test results is made between the TSR ratios. Figure 4(a,b) shows the TSR ratios of each specimens without/with modifier for the high absorptive and low absorptive aggregate, respectively. It can be concluded from the Figure 4 that the TSR values do not satisfy the criteria of at least 80% after 24 h conditioning whether they are modified or not.

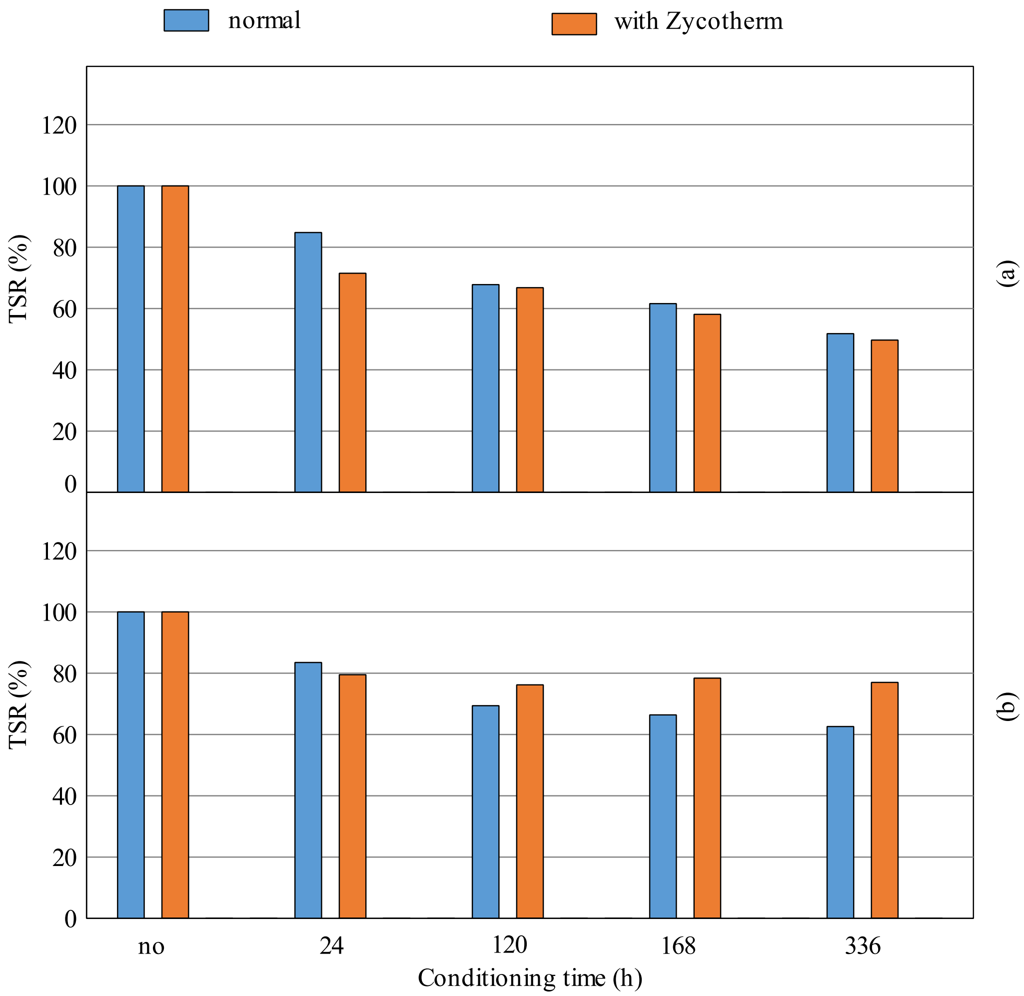


Figure 4. TRS ratios: (a) high absorptive aggregate, (b) low absorptive aggregate

From the Figure 4 it can be also seen that, even though, the zycotherm modification increased the IDT strength of the both aggregate types, the TSR ratios are decreased for the high absorptive aggregate, but not for the low absorptive one. Meaning the increase in IDT results of conditioned specimens over unconditioned ones are different for the high and low absorptive aggregates. It is believed that the main reason is the difference between origin and absorption rate of the two aggregates. Zycotherm behaves differently between these two sources of basalt aggregates.

4.2. Hamburg wheel-track test results

The measured ruts at each loading cycle, along with the air voids of the sample after the compaction are given in Table 5. From the table, the mixtures of low absorptive aggregate seem to develop smaller rutting than those of high absorptive ones. In terms of the effect of zycotherm, both mixture types, developed smaller rutting than their control mixtures. The improvement in the rutting resistance for high and low absorptive aggregates are 5.9% and 11.6%, respectively.

Table 5. Hamburg wheel-track test results

		Rut depth (Specimen thickness: 50 mm)			
		Type 1 aggregate		**Type 2 aggregate**	
	Parameter	**Without additive**	**With additive**	**Without additive**	**With additive**
	Air void, %	5.697	5.378	5.657	5.678
Rut depth (mm)	1000 cycle	2.05	2.20	1.50	1.75
	3000 cycle	3.00	3.15	2.15	2.20
	5000 cycle	3.75	3.80	2.80	2.75
	10 000 cycle	4.90	4.80	3.40	3.12
	15 000 cycle	5.65	5.50	3.90	3.55
	20 000 cycle	6.40	6.05	4.25	3.90
	30 000 cycle	**7.34**	**6.91**	**4.93**	**4.36**

5. CONCLUSIONS

The effect of zycotherm, a liquid, nano-organosilane, anti-stripping additive, was evaluated on the tensile strength and rutting resistance of asphalt samples. A detailed experimental program was scheduled to evaluate how the silane based additive effects the performance properties of mixtures. The testing program included two types of basalt aggregates; high and low absorptive. The testing conditions were also revised by extending the conditioning times. Based on the test results, the following conclusions can be made:

- Zycotherm increased the indirect tensile strength of the mixtures with both type of aggregates. The relative improvement in the IDT strength is around 24.7% for the high absorptive aggregate and 12.4% for the low absorptive aggregate. The average strength increases are 1.4 kg/cm^2 and 1.0 kg/m^2 for high and low absorptive aggregates, respectively. The conditioning time for the same strength value is extended around 3 times of the control mixtures, when the samples are modified.
- Even though, The TSR ratios of high absorptive aggregate are decreased, when zycotherm is used, they are generally higher for the low absorptive aggregate. The difference between the origin and physical characteristics of these two aggregates are believed to be the main reason. For both type of aggregates, the TSR values do not satisfy the criteria of at least 80% after 24 h conditioning whether they are modified or not.
- In terms of rutting performance, in general, the mixtures of low absorptive aggregate yielded smaller rutting than those of high absorptive ones. When zycotherm was used, both mixture types developed smaller rutting than their control mixtures, that is 5.9% smaller rutting for high and 11.6% smaller rutting for low absorptive aggregate.

6. REFERENCES

[1] Arabani, M., Roshani, H., & Hamedi, G. H. (2011). Estimating moisture sensitivity of warm mix asphalt modified with zycosoil as an antistrip agent using surface free energy method. Journal of Materials in Civil Engineering, 24(7), 889-897.

[2] Nejad, F. M., Azarhoosh, A. R., Hamedi, G. H., & Azarhoosh, M. J. (2012). Influence of using nonmaterial to reduce the moisture susceptibility of hot mix asphalt. Construction and Building Materials, 31, 384-388.

[3] Ameri, M., Kouchaki, S., & Roshani, H. (2013). Laboratory evaluation of the effect of nano-organosilane anti-stripping additive on the moisture susceptibility of HMA mixtures under freeze–thaw cycles. Construction and Building Materials, 48, 1009-1016.

[4] Shafabakhsh, G. H., Faramarzi, M., & Sadeghnejad, M. (2015). Use of Surface Free Energy method to evaluate the moisture susceptibility of sulfur extended asphalts modified with antistripping agents. Construction and Building Materials, 98, 456-464.

[5] Ziari, H., Mirzababaei, P., & Babagoli, R. (2016). Properties of bituminous mixtures modified with a nano-organosilane additive. Petroleum Science and Technology, 34(4), 386-393.

[6] Mirzababaei, P. (2016). Effect of zycotherm on moisture susceptibility of Warm Mix Asphalt mixtures prepared with different aggregate types and gradations. Construction and Building Materials, 116, 403-412.

[7] Ayazi, M. J., Moniri, A., & Barghabany, P. (2017). Moisture susceptibility of warm mixed-reclaimed asphalt pavement containing Sasobit and Zycotherm additives. Petroleum Science and Technology, 35(9), 890-895.

[8] Ameri, M., Vamegh, M., Naeni, S. F. C., & Molayem, M. (2018). Moisture susceptibility evaluation of asphalt mixtures containing Evonik, Zycotherm and hydrated lime. Construction and Building Materials, 165, 958-965.

[9] Sanij, H. K., Meybodi, P. A., Hormozaky, M. A., Hosseini, S. H., & Olazar, M. (2019). Evaluation of performance and moisture sensitivity of glass-containing warm mix asphalt modified with zycothermTM as an anti-stripping additive. Construction and Building Materials, 197, 185-194.

[10] Behbahani, H., Ziari, H., Kamboozia, N., Khaki, A. M., & Mirabdolazimi, S. M. (2015). Evaluation of performance and moisture sensitivity of glasphalt mixtures modified with nanotechnology zycosoil as an anti-stripping additive. Construction and Building Materials, 78, 60-68.

[11] Ibrahim, I., & Mehan, H. N. A. (2015). The effect of nano-materials on hot mixture "asphalt-concrete". Open Journal of Civil Engineering, 5(04), 419.

[12] Mirzababaei, P., Nejad, F. M., & Vanaei, V. (2017). Investigation of rutting performance of asphalt binders containing warm additive. Petroleum Science and Technology, 35(1), 79-85.

[13] Faramarzi, M., Golestani, B., & Lee, K. W. (2017). Improving moisture sensitivity and mechanical properties of sulfur extended asphalt mixture by nano-antistripping agent. Construction and Building Materials, 133, 534-542.

[14] Rohith, N., & Ranjitha, J. (2013). A study on marshall stability properties of warm mix asphalt using zycotherm a chemical additive. International Journal of Engineering Research & Technology (IJERT), 2(7).

[15] Behbahani, H., Ayazi, M. J., & Moniri, A. (2017). Laboratory investigation of rutting performance of warm mix asphalt containing high content of reclaimed asphalt pavement. Petroleum Science and Technology, 35(15), 1556-1561.

[16] Hasan, M. R. M., Hamzah, M. O., & Yee, T. S. (2017). Performance characterizations of asphalt binders and mixtures incorporating silane additive ZycoTherm. In AIP Conference Proceedings (Vol. 1892, No. 1, p. 090001). AIP Publishing.

[17] Ziari, H., Naghavi, M., & Imaninasab, R. (2018). Performance evaluation of rubberised asphalt mixes containing WMA additives. International Journal of Pavement Engineering, 19(7), 623-629.