Research Article

The effect of different deicing solutions on the moisture susceptibility of asphalt mixture

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Abstract
The present research studies the effectiveness and efficiency of solutions such as sodium chloride, magnesium chloride and potassium acetate on asphalt pavement to reduce the damage caused by moisture on asphalt pavement in winter. To prevent the stripping problem in asphalt, Nano-Zycotherm with three quantities corresponding to 0.1%, 0.2% and 0.3% weight of bitumen is used in this study. Under the saturated condition with the above solutions, the indirect tensile test performs by applying a freeze–thaw cycle as a means to measure the amount of moisture susceptibility. The results indicate that the asphalt mix containing 0.3% Nano-Zycotherm has a higher indirect tensile strength and tensile strength ratio than asphalt mix containing 0.1% and 0.2% Nano-Zycotherm. Accordingly, Magnesium chloride solution is the most effective deicing material to improve the indirect tensile strength and durability of asphalt pavements when faced with moisture and ice.

Article highlights

- The presence of Nano-Zycotherm in asphalt leads to its increased resistance against stripping.
- The use of Sodium chloride and potassium acetate deicing solutions causes some damages in asphalt.
- Considering different solutions, magnesium chloride has the best performance against asphalt stripping.

Keywords Deicing · Sodium chloride · Magnesium chloride · Potassium acetate · Nano-zycotherm · Indirect tensile strength

1 Introduction

Providing optimal service levels by carrying out efficient road maintenance with the highest safety and lowest cost for use of the road is considered to be a major problem in the transportation system. This level of service is threatened by natural and atmospheric factors throughout the winter and cool weather. Therefore, solving the problems caused by snowfall and rain and freezing the road surface, the incidence of the blizzard, safety and visual limitation along the way, especially in mountainous areas are regarded as the most important challenges in road management and maintenance.

In most cases, a mix of chemicals, gravel and sand particles is used as a part of winter road maintenance operations for deicing and preventing road freezing. Above all, salt is a chemical material used for deicing and preventing road freezing. During the following hours and days, some part of chemicals, gravel and sand particles, which are used in winter road maintenance procedure, stay on

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the road surface, some part of them enter the air as small particles and the remaining enters into the underground water flow and soil porosity as a solution; consequently, they cause negative effects and environmental and technical damages. Concerning the freeze–thaw cycle, the use of such materials to deice the asphalt surface reduces the service life of pavements. In resumption, the following investigation can be mentioned as technical literature.

Compared to the deicing and sandblasting, the anti-freezing strategy along with cost-saving improves the level of service, reduces the chemicals, and increases the safety factor. In contrast to other methods of winter maintenance, the freezing procedure that uses liquid chemicals is more sensitive to weather [1]. Using chloride—based products has raised concerns about their negative impact on the metal parts of vehicles [2] and transportation infrastructures and the environment [3, 4]. Researches indicate that the detrimental environmental impacts of abrasives outweigh those of chloride. A salt mix and snow cleaning are considered to be the best practices to manage the snow and ice [4]. Chloride-based ice control products may threaten the durability of concrete structures and road pavement in three ways: physical damage by salt [5] a chemical reaction between the antifreeze and concrete [6]; anti-freeze increased aggregate reaction [2]. Parking, pavement and road equipment that are kept on the roadside are exposed to the corrosive effects of chloride, as well [3]. Chloride-based salts are the most common chemical, which are used to reduce the freezing point in the winter maintenance procedure. Chloride is known as the most corrosive substance for road winter maintenance [2]. Since the 1960s, due to the extensive use of chloride-based products to control ice and snow, the environmental impact is also regarded as an important subject of research. For instance, the most common concerns associated with the use of chloride salts include roads and surrounding soils saltiness, environmental and roadsides degradation, penetration of chloride ion and cation into the soil and drinking water [7]. The extensive use of salt on the highways causes serious corrosion problems on the asphalt pavement in addition to the environmental damages [8]. Studies show that salt reduces the hardness of Mastics (bituminous mortar) and it affects its visco—elasticity properties [9]. Earlier studies indicate that salt has a direct impact on the strengths of asphalt by affecting bitumen material and emulsification of sticky substance [10]. Many state departments of transportation (DOT) use sodium chloride and magnesium chloride in the saltwater solution for anti-freezing, which have a better performance in melting ice at low temperatures than just salty water [11]. Besides the chlorides, acetates such as potassium acetate (KAC) and calcium magnesium acetate (CMA) are used for anti-freezing, which are more expensive. As contrasted to the chlorides, KAC and CMA are more effective, less corrosive, and are not harmful to the environment [2]. Studies conducted on the Wisconsin State roads between 1992 and 1995 show that the number of cracks and pavement damage increases between 25 to 35 percent, depending on the first conditions of the road after repeating freezing three times and winter road maintenance (spraying chemicals) on the pavement surface [12]. From 1970 to 1980, it was assumed that moisture imposes an adverse effect on the asphalt pavement. Stripping, early rutting, shoulder drop are the negative effects caused by moisture and ice, which are the reasons for many other fundamental problems in the pavement. These negative effects caused by the presence of moisture in many pavements are the most well-known problems and challenges regarding asphalt pavement [13]. In recent years, the nanomaterial is used in changing asphalt [14]. Tao et al. evaluated the performance of deicing asphalt mixtures with anti-icing additives and proposed a solution to reduce the negative effects of anti-icing additives on the engineering properties of asphalt mixtures. They used high-temperature wheel tracking test, low-temperature three-point bending beam test, Marshall test and splitting tests to evaluate the engineering properties of deicing asphalt mixtures. According to their finding, the addition of polyester fibers can compromise the negative effects of anti-icing additives to get fiber-reinforced deicing asphalt mixtures with satisfied engineering property [15]. Tao et al. used deicing asphalt mixtures produced by replacing mineral fillers with deicing agents in the asphalt mixture to develop high-performance deicing asphalt mixture. They concluded that the high-performance modifier increases cracking resistance and high-temperature rutting resistance of asphalt binder. They also found that as the content of deicing agent increases the deicing effectiveness is stronger while the mechanical performance degraded [16]. As indicated by research conducted on determining the optimal value of Nano-Zycotherm that is added to the bitumen and asphalt, Nanno-Zycotherm increases resistance when faced with moisture, rutting, exhaustion and cracks at low temperature [17]. Moghadas Nejad et al. [18] conducted a study to evaluate the effect of Zycosoil on resistance when faced with moisture in asphalt, and they concluded that Zycosoil increases fatigue life and leads to a better resistance when faced with moisture. Rohith and Ranjitha [19] studied the Marshall Stability properties of dense hot asphalt and warm asphalt containing Nano-Zycotherm. Their results showed that the Marshall Stability properties of warm asphalt containing 0.1 percent Nano-Zycotherm have a more proper performance. Superpave Bitumen and asphalt mixes tests were performed on the asphalt with bitumen containing Nano soil. Their finding indicated that adding 0.5 percent Nano soil to bitumen increases resistance to rutting and fatigue life and the value of TSR [20].

The present research studies the impact of using deicing solutions, including sodium chloride, magnesium chloride and potassium acetate on the asphalt durability when faced with moisture and freeze–thaw cycle. The effect of using Nano-Zycotherm additive to prevent the asphalt stripping phenomenon due to using/not using the aforementioned deicing solutions is also investigated. This study is mainly aimed to find the most proper deicing solution that improves resistance when faced with pavement moisture.

The remainder of this paper is structured as follows. The first section is dedicated to the literature review. Section two presents the technical specifications of the consumed materials (bitumen, aggregates, additives, and deicing solutions). Section three addresses the sample preparation, the process of determining the optimal bitumen, and the tests used to measure moisture susceptibility. The fourth section provides the results of the tests, models, and statistical analysis. At last, the conclusions are presented in the fifth section.

2 Materials specifications

2.1 Bitumen specifications

In this study is used bitumen 60/70 to make asphalt specimens. Table 1 presents technical Specifications of used bitumen.

2.2 Aggregates specifications

In this study, limestone aggregates are used to make asphalt specimens. Aggregates grading is done according to Fig. 1. Table 2 presents physical and technical properties of used limestone aggregates.

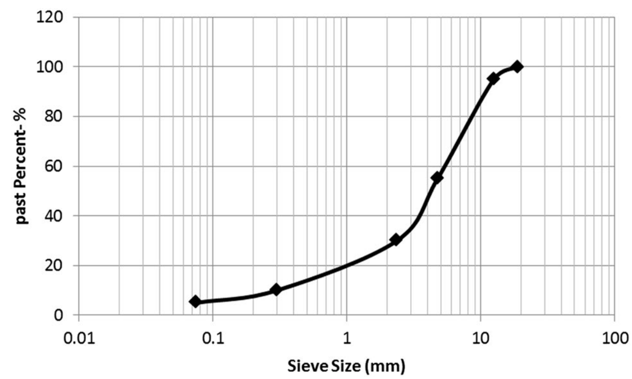


Fig. 1 Selected grading curve

2.3 Asphalt additive specifications

Zycotherm is used as an additive to improve the properties of asphalt. Zycotherm is just the same as Zycosoil, which its specifications have been enhanced in all cases; Zycosoil is an organosilane combination, which is formed from Silanol groups (Si–OH). Silanol groups are active and they form a siloxane bond (Si–O–Si) with the silanol groups of mineral surface such as surface materials, soil, and gravel. These siloxane bonds are hydrophobic and are not washed, because they create a chemical bond with surface materials. Figures 2 and 3 show how Zycosoil is bonded with materials and how it affects surface hydrophobic of material [20].

Zycotherm nanotechnology excretes permanent water on the aggregates through the layers with dimensions less than 100 mm, which are placed on the aggregate; and it

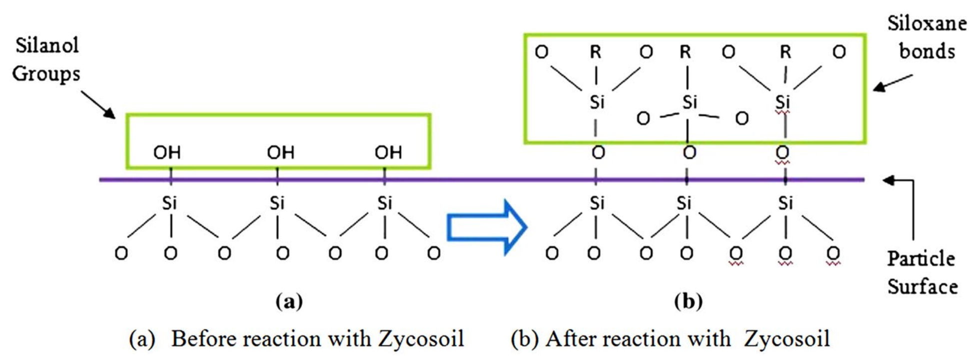
Table 1 Specifications of the Consumed Pure Bitumen

Experiments	Test method		Results of experiment	Results range of experiment	
	AASHTO	ASTM		Min	Max
Specific gravity at 25 °C (gr / cm3)	T228	D70	1.018	–	–
Penetration Grade at 25 °C	T49	D5	64	60	70
Softening Point (Ring and Ball)	T53	D36	50.5	49	56
Ductility Of Bitumen at 25 °C (cm)	T51	D113	> 100	100	–
Solubility in Carbon tetrachloride (%)	T44	D2042	99.7	99	–
Flash point (° C)	T48	D92	292	232	–
Kinematic Viscosity at 120 °C (CentiStokes)	T201	D2170	756	–	–
Kinematic Viscosity at 135 °C (CentiStokes)	T201	D2170	326	–	–
Kinematic Viscosity at 160 °C (CentiStokes)	T201	D2170	137	–	–
bitumen loss on heating (%)	–	–	0.03	–	0.8

Table 2 Aggregate characteristics

Specification		Test results	
		Fine aggregate mix	Coarse aggregate mix
Sand Equivalent Value (%)		70	–
Los Angeles abrasion value (%)		–	20
Percentage of Fractured Particles in one side (%)		–	98
Percentage of Fractured Particles in two sides (%)		–	95
Bitumen coating aggregate (%)		–	> 95
Aggregate particle shape	Flakiness index	– –	9
	Elongation index	–	16
Weight loss versus sodium sulfate (%)		–	0.5

Fig. 2 Zycosoil bonds with material surface, before reaction with zycosoil (**a**), after reaction with zycosoil (**b**)



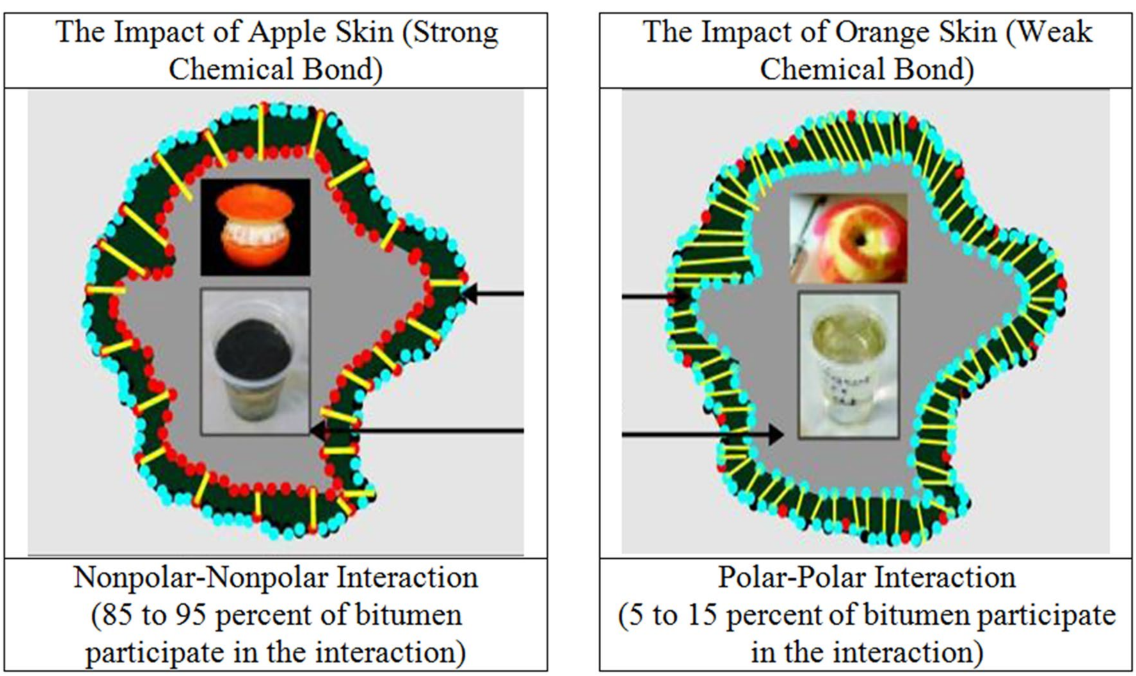


Fig. 3 The Impact of zycotherm chemical bond comparison

Table 3 Physical and chemical properties of Zycotherm

Properties	Zychotherm
Color	pale yellow
Form	Liquid
Freezing point	5–7°C
Flash Point	> 80°C
Viscosity (at 25°C)	< 0.3 Pa.s

forms the siloxane bond that is the strongest link with the nature and normal conditions persist for years.

Physical and chemical properties of Zycotherm used in this study are presented in Table 3.

2.4 Deicing solutions

In this research the chemical solutions that are used for Deicing are sodium chloride (NaCl), magnesium chloride ($MgCl_2$) and potassium acetate (KAC).

3 Experimental setup and procedure

3.1 How zaycotherm mix with bitumen

In wet process, high-speed stirrer apparatus is used to blend Zaycotherm in bitumen. Zycotherm is added directly to bitumen by weight of bitumen at three 3 different percentages (0.1%, 0.2% and 0.3%) while the bitumen at reaction temperature of 135 C and a reaction speed of 3500 rmp for 10 min. For getting the desired result, Zaycotherm should be added drop by drop while stirring.

3.2 How to make asphalt

Marshall Compactor was used to fabricate cylindrical samples with a diameter 100 mm and approximate height 67 mm, which weight 1200 g and compacted at 75 hammer blows per face of the samples. Samples at bitumen contents of 3.5%,4%, 4.5%, 5%, 5.5%, and 6% were used to determine optimal bitumen content of control, pure bitumen with 0.1% Nano-zychotherm (Z-0.1%), pure bitumen with 0.2% Nano-zychotherm (Z-0.2%) and pure bitumen with 0.3% Nano-zychotherm (Z-0.3%) mixtures. Three identical samples were prepared for each percentage and the average was calculated as the measured value of different tests.

3.3 Marshall test

Marshall Test results are used to find the best bitumen content of asphalt mixes. For this purpose, cylindrical specimens have been used with 101.6 mm diameter and 63.5 mm height and the material is compacted with 75 blows per side of the hammer. In this method, first specimens are heated to 60 ± 1 °C for 30–40 min in a water bath, and then the specimens are take out from the water bath and place between upper and lower cylindrical segments of Marshall machine. Load is increased at a loading rate of 50 mm per minute until it reaches a maximum. The maximum load that leads to specimen failure is recorded. During the loading, the flow as recorded on the flow meter in units of mm was also noted. This maximum force is defined as Marshall Endurance or Marshall Strength.

3.4 Indirect tensile strength test

LOTTMAN method according to AASHTO-T283 standard is used to investigate the effect of moisture on the laboratory specimens and to assess resistance against stripping. Tensile strength is the maximum load that an asphalt specimen can withstand before cracking. Six compacted dry and wet asphalt specimens, containing between 6.5 to 7.5% of the air voids, are made to ITS test on each anti-freezing solutions. To simulate the real condition of the pavement that is exposed the snow and sun; the specimens are also exposed to a freeze–thaw cycles. To this end, first, the specimens are saturated with anti-freezing solutions to a level between 55 and 80%. Then they are placed in freezer at a temperature of 18 °C for 18 h and as soon as the specimens are placed in the water bath at a temperature of + 60 °C for 24 h.

ITS test involves loading a cylindrical specimen in the diametrical direction with a compressive load at a constant rate acting parallel to and along the vertical diametrical direction of the specimen through two opposite loading strips (Fig. 4). The vertical applied load causes deformations perpendicular to loading plane. This test is typically for determination of mixtures properties and structural evaluation of pavements. It is used to determine the tensile strength of asphalt mixtures as well as resistance against cracking [21]. ITS is calculated according to the following formula:

$$S_t = \frac{2P}{\pi tD} \tag{1}$$

In the Eq. 1, S_t is tensile strength (kpa); P is maximum load (N); t is specimen thickness (mm) and D is Specimen Diameter (mm).

TSR is defined as the coefficient moisture durability index and obtained by dividing the indirect tensile strength of a specimen in moist conditions to the indirect tensile strength of specimen in dry conditions [22]. TSR less than 80% is not recommended and to improve it, using anti-stripping additives are recommended.

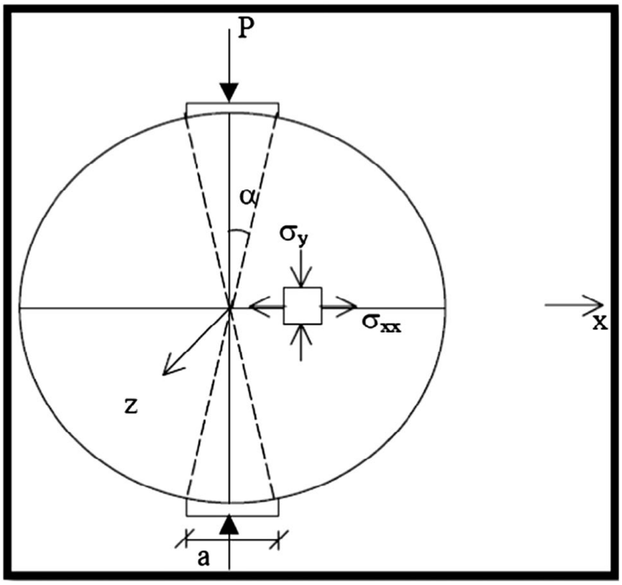


Fig. 4 Schematic of indirect tensile strength (ITS) loading

$$\mathrm{TSR} = \frac{S_2}{S_1} \tag{2}$$

In the Eq. 2, TSR is tensile strength ratio; S_1 is the indirect tensile strength of specimen in dry conditions (kpa) and S_2 is the indirect tensile strength of a specimen in moist conditions (after enduring a freeze–thaw cycle) (kpa).

In this phase of freeze–thaw cycle, solutions as sodium chloride (NaCl), magnesium chloride ($MgCl_2$) and potassium acetate (KAC) with a ratio of 1:15 with water is used to saturate and prepare specimens in this study. The test is carried out under a freeze–thaw cycle for four types of bitumen and four types of solutions for saturation. The test is also repeated three times for each mixture.

4 Results and discussion

4.1 Results of marshall test and determination of optimum bitumen content

Based on the results of Marshall Test (Fig. 5) and publication of asphalt institute recommendations (MS-2), the optimal value of 4.3% has been selected.

With the aim of determining the optimal bitumen, the diagrams are first drawn, which indicate the strength, flow, actual specific weight, the empty space between the aggregate particles and the empty space of the compacted samples in different percentages of bitumen (3.5, 4, 4.5, 5, 5.5, 6, and 6.5). As indicated by the Marshall mixing diagrams (Fig. 5), the optimal bitumen content determines based on the contents included in the recommendations of Asphalt Institute MS-2, according to the bitumen percentage such as air voide 4.5% equal to 4.3%, and other parameters of asphalt mixture is controlled for 4.3% of bitumen, which were within the acceptable range.

4.2 The results of the indirect tensile strength

Indirect Tensile Strength (ITS) and Indirect Tensile Ratio on all specimens and under each condition are given in Figs.6, 7, 8 and 9. According to the diagrams, the following results are obtained:

Asphalt specimens with Zycotherm showed more tensile strength than specimens with pure bitumen when they were saturated with municipal water. An increase in the value of Zycotherm from 0.1% to 0.3% has led to increase solutions of sodium chloride, magnesium chloride and potassium acetate and the tensile strength of specimens under dry conditions and when saturated with municipal water.

The indirect tensile strength of mixes with 0.3% Nano-zychotherm under dry conditions and saturated with pure water has the best value and equal to 808.3 and 700.3 kg for dry and saturated conditions. It as well has a TSR equivalent to 86.64%. Mixes with 0.3% Nano-zychotherm have the highest indirect tensile strength and TSR under conditions of saturated with solutions of sodium chloride, magnesium chloride and potassium acetate.

Indirect tensile strength of mixes with 0.3% Nano-zychotherm for saturated conditions under solutions of sodium chloride, magnesium chloride and potassium acetate is 661, 722.7 and 701.3 and the value of TSR is equivalent to 81.76, 89.41 and 86.76, respectively. TSR value in all mixes containing Nano-zychotherm is over 80% and they had an acceptable duration against the freeze–thaw cycle.

Figure 8 shows the indirect tensile strength difference (ITS) of mixes with 0.1%, 0.2% and 0.3% Nano-zychotherm under conditions of saturated with various solutions compared to the mix with pure bitumen under saturated condition. The average ratio of indirect tensile strength under conditions of saturated with solution of magnesium chloride in asphalts with pure bitumen and/or Zychotherm has been within the allowable range at all tested percentages so that this ratio for all specimens under this condition has been more than the allowed least value i.e. 0.80.

Asphalt mix saturated with a solution of sodium chloride and potassium acetate have a lower indirect tensile strength and durability than asphalt mixed saturated with municipal water when faced with moisture and ice. Also, asphalt mix saturated with magnesium chloride solution has a higher indirect tensile strength and durability than asphalt mixed saturated with municipal water when faced with moisture and ice. Reason for the improved condition

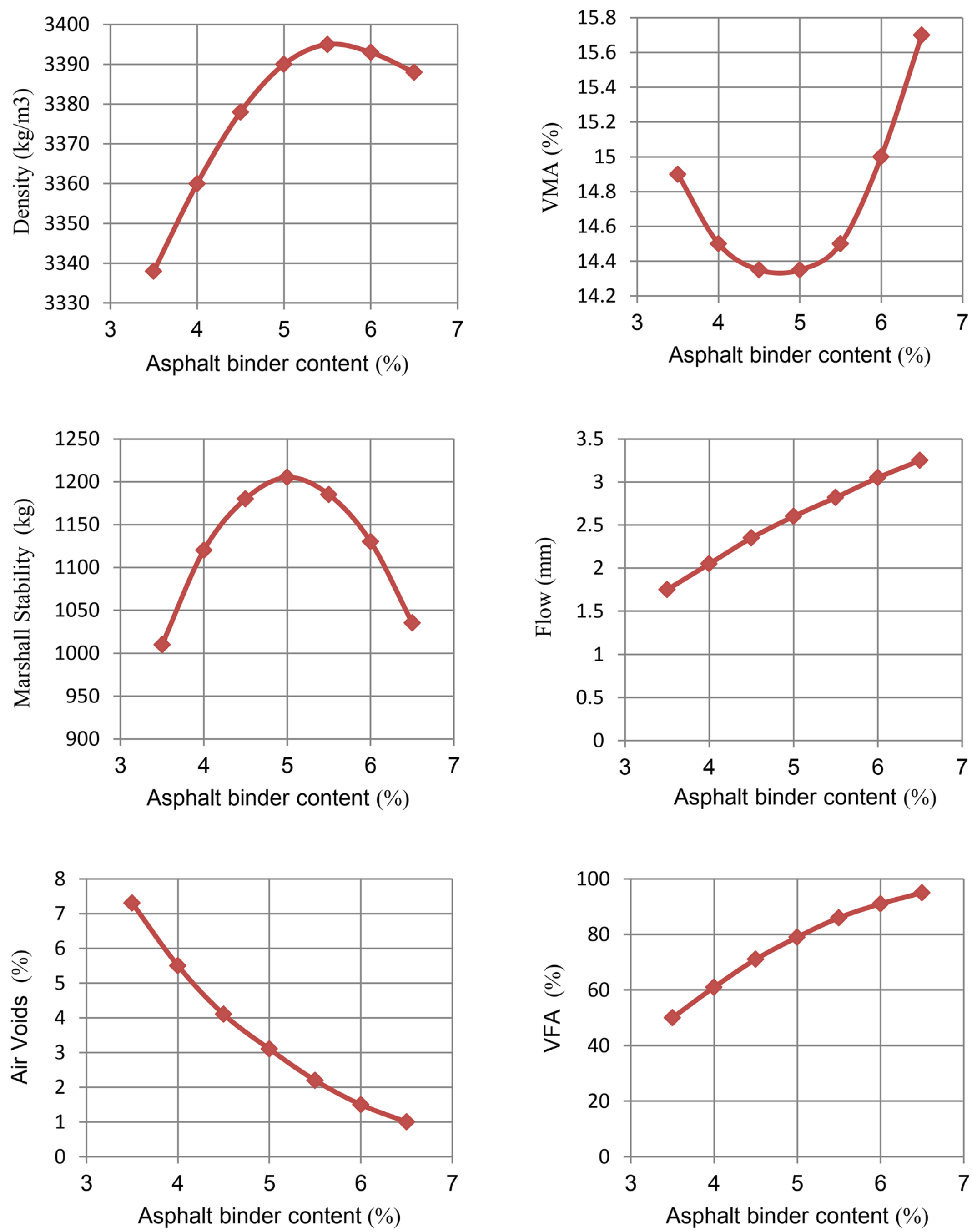


Fig. 5 Determine the asphalt binder content based the Marshall Mix design method

of asphalt with adding Zycotherm to bitumen when faced with moisture and the freeze–thaw cycle is an increase in bitumenphilic property of bitumen with aggregates. Zycotherm makes a permanent and strong bond between bitumen and aggregate. Bitumen containing Zycotherm completely covers fine pores and porosities on the surface of aggregates. These siloxane bonds are hydrophobic and they are not washed due to the chemical bond that they make with the material surface.

According to the results of moisture susceptibility test, using any of these three de-icing agents increases the tensile strength in the wet case. Deicing solutions cause melting ice due to reducing the temperature of icing and preventing the formation of ice minerals. Solutions from melting snow are combined with deicing solutions and ingress into the surface layer as well as asphalt pores of asphalt. This combined solution and water gradually weakens the bond strength between the

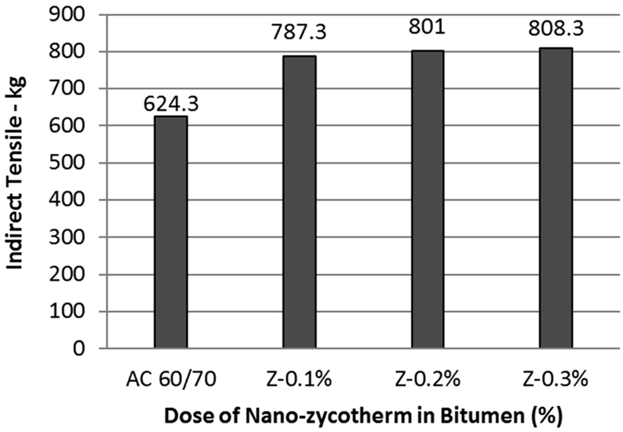


Fig. 6 Indirect Tensile Strength (ITS) of all mixes under dry condition

aggregates and causes the aging and fragility of bitumen. Regarding the results, using potassium acetate and sodium chloride result in aging and fragility of bitumen of asphalt, while magnesium chloride improves the aging and fragility of bitumen and owns greater ITS comparing to other samples.

4.3 Statistical studies

Statistical studies are conducted on various mixtures under different deicing solutions. Regression model is used to estimate TSR. At last, the sensitivity analysis of these models is performed by Minitab software.

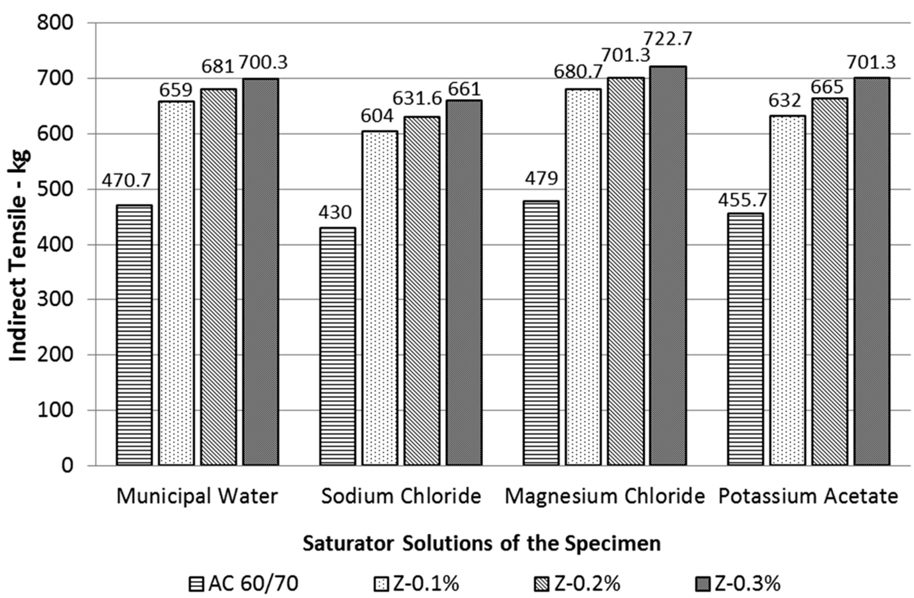
4.3.1 TSR regression models

The results of TSR regression models for all mixtures indicate various percentages of zycotherm under different deicing solutions, which are given in Figs. 10, 11, 12 and 13. In Figs. 10, 11, 12 and 13, the horizontal axis is the zycotherm value in percentage and the vertical axis is the TSR value in percentage.

4.3.2 The statistical analysis of TSR regression models

SPSS Statistics will generate quite a few tables of output for the regression analysis. In this study, the three main tables are provided. The first table of interest is the Model Summary table. This table is used to determine how well a prediction model fits into actual data. One of the key factors in this table is R^2, which is the proportion of variance in the dependent variable. As shown in Tables 4, 5, 6 7, R^2 in all models is above 0.9, which is a good level of prediction. The second table is ANOVA table, which shows that the independent variables statistically significantly predict the dependent variable. The *F* ratio and "Sig." in this table are the major criteria to check the appropriateness and significance of the model. As the Tables 4, 5, 6, 7 the *F* value is high and "Sig." is less than 0.05, it can be concluded that the existing models are significant with 0.95% confidence level. In the third table, the coefficients of the independent variables in the proposed models are presented. As the Tables 4, 5, 6, 7 the "Sig." is less than 0.05, so it can be concluded that the independent variables are significant with 0.95% confidence level.

Fig. 7 Indirect Tensile Strength (ITS) of all mixes under moist condition (saturated with different deicing solutions)



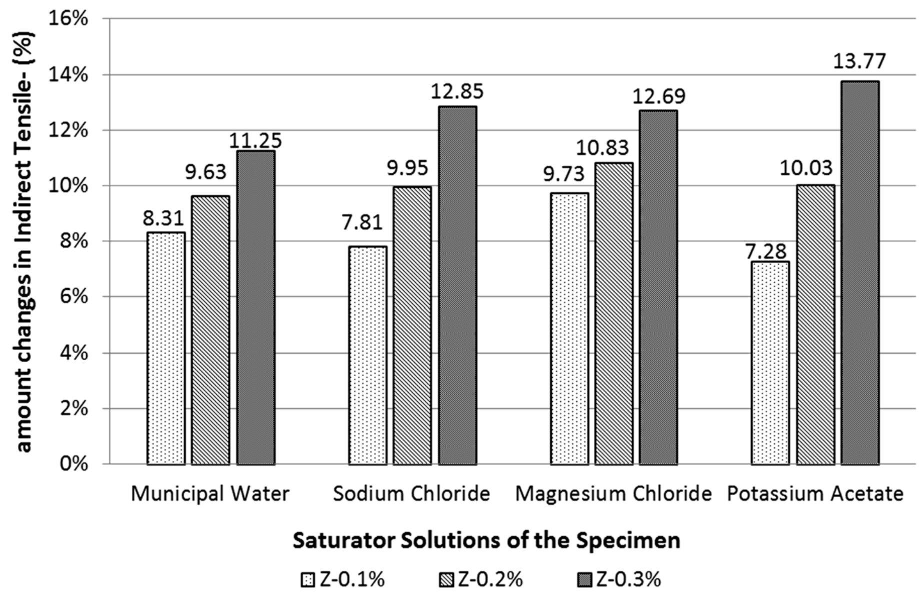


Fig. 8 Indirect Tensile Strength ratio of mixes with nano-zychotherm Pure Bitumen to mixes with pure bitumen under moist conditions (saturated with different deicing

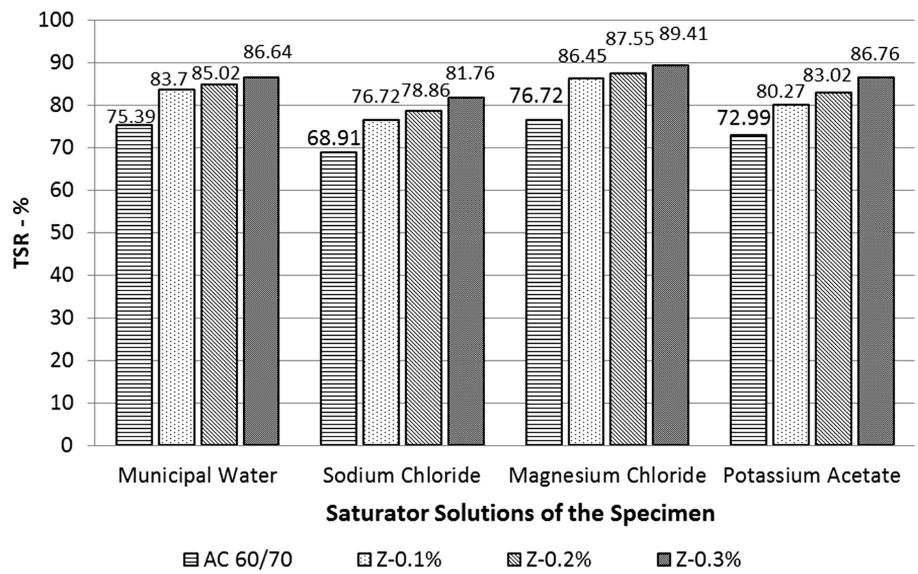


Fig. 9 Tensile Strength Ratio (TSR) of all mixes

5 Conclusions

This research aimed to provide a new deicing solution and anti-stripping material that causes the least moisture damage to the asphalt surface. It is assumed that the use of nano-zycotherm increases the resistance to moisture damage. Indirect tensile test in dry and saturated conditions has been used to study the stripping. Moreover, this research also used four solutions, including municipal water, sodium chloride, magnesium chloride and potassium acetate to saturate the specimens and Nano-Zycotherm has been applied by three values of 0.1, 0.2 and 0.3 bitumen weight percent of specimens. Results show that, Asphalt specimens containing Zycotherm have a higher TSR and tensile strength than specimens containing pure bitumen in both dry and saturated conditions; thus, it increases resistance against stripping. Results also indicate that Asphalt specimen with 0.3% Zycotherm shows the best performance, and it has the highest TSR and indirect tensile strength in both dry and saturated conditions in all solutions. Moreover, Deicing with the solutions of sodium chloride and potassium acetate has a negative and damaging impact on the asphalt compared to the municipal water and it leads to the phenomenon of stripping and reduces the indirect tensile strength of asphalt. Eventually, the solution of magnesium chloride has the best performance among

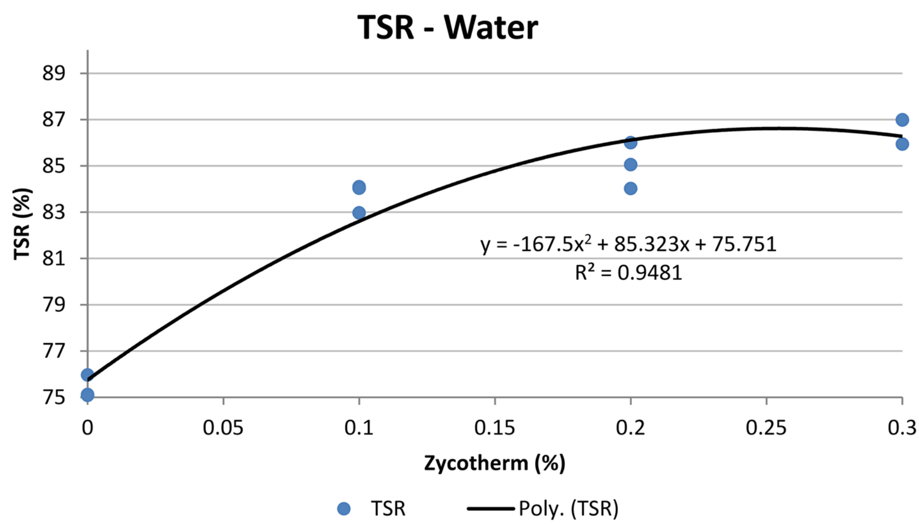


Fig. 10 Regression model of TSR for samples saturated with Water

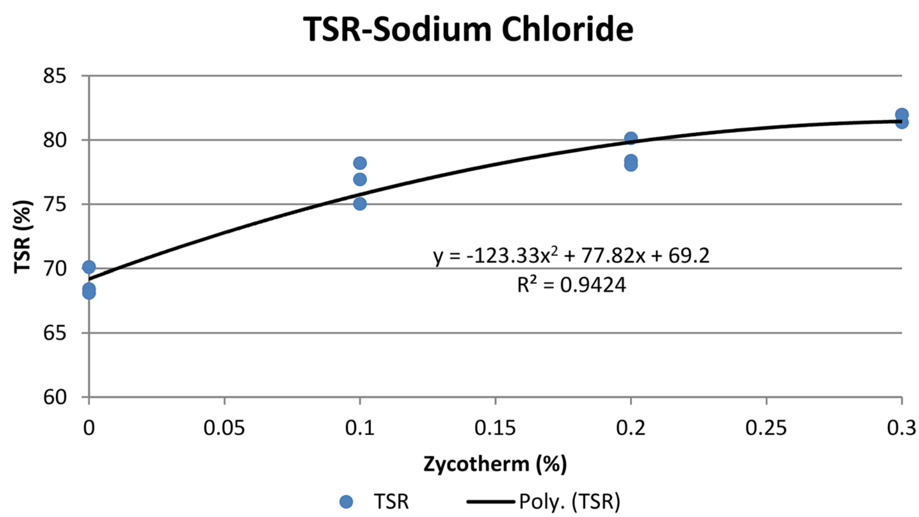


Fig. 11 Regression model of TSR for samples saturated with sodium chloride solution

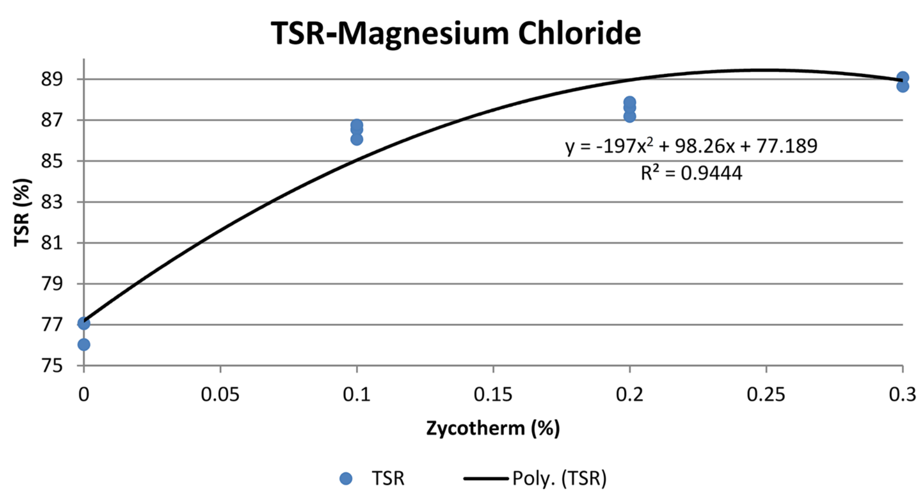


Fig. 12 Regression model of TSR for samples saturated with magnesium chloride solution

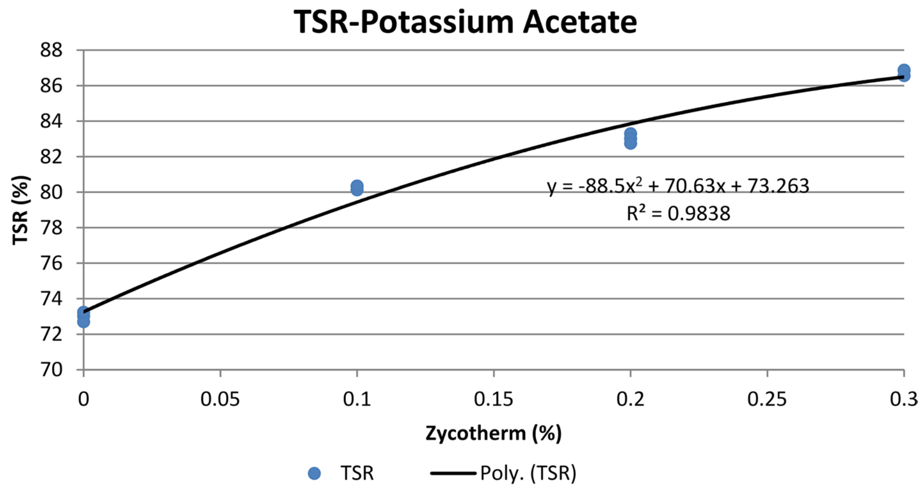


Fig. 13 Regression model of TSR for samples saturated with potassium acetate solution

Table 4 Statistical analysis of TSR regression model—Water

R	R square	Adjusted R square	Std. Error of the estimate		
Model summary					
.974	.948	.937	1.152		
The independent variable is Zycotherm					
	Sum of squares	df	Mean square	F	Sig
ANOVA					
Regression	218.188	2	109.094	82.268	.000
Residual	11.935	9	1.326		
Total	230.123	11			
The independent variable is Zycotherm					
	Unstandardized coefficients		Standardized coefficients	t	Sig
	B	Std. error	Beta		
Coefficients					
Zycotherm	85.323	10.407	2.178	8.199	.000
Zycotherm** 2	−167.500	33.243	−1.339	−5.039	.001
(Constant)	75.751	.648		116.896	.000

Table 5 Statistical analysis of TSR regression model—Sodium Chloride solution

R	R square	Adjusted R square	Std. error of the estimate
Model Summary			
.971	.942	.930	1.350

The independent variable is Zycotherm

	Sum of squares	df	Mean square	F	Sig
ANOVA					
Regression	268.194	2	134.097	73.568	.000
Residual	16.405	9	1.823		
Total	284.599	11			

The independent variable is Zycotherm

	Unstandardized coefficients		Standardized coefficients	t	Sig
	B	Std. error	Beta		
Coefficients					
Zycotherm	77.820	12.201	1.787	6.378	.000
Zycotherm ** 2	−123.333	38.974	−.886	−3.165	.011
(Constant)	69.200	.760		91.084	.000

Table 6 Statistical analysis of TSR regression model—Magnesium Chloride solution

R	R square	Adjusted R square	Std. error of the estimate
Model Summary			
.972	.944	.932	1.345

The independent variable is Zycotherm

	Sum of squares	df	Mean square	F	Sig
ANOVA					
Regression	276.597	2	138.298	76.441	.000
Residual	16.283	9	1.809		
Total	292.880	11			

The independent variable is Zycotherm

	Unstandardized Coefficients	Std. error	Standardized coefficients	t	Sig
	B		Beta		
Coefficients					
Zycotherm	98.260	12.155	2.224	8.084	.000
Zycotherm ** 2	−197.000	38.829	−1.396	−5.074	.001
(Constant)	77.189	.757		101.979	.000

Table 7 Statistical analysis of TSR regression model—Potassium Acetate solution

R	R square	Adjusted R square	Std. error of the estimate		
Model Summary					
.992	.984	.980	.743		
The independent variable is Zycotherm					
	Sum of Squares	df	Mean Square	F	Sig
ANOVA					
Regression	300.856	2	150.428	272.594	.000
Residual	4.967	9	.552		
Total	305.822	11			
The independent variable is Zycotherm					
	Unstandardized coefficients		Standardized coefficients	t	Sig
	B	Std. error	Beta		
Coefficients					
Zycotherm	70.630	6.713	1.564	10.521	.000
Zycotherm ** 2	−88.500	21.444	−614	−4.127	.003
(Constant)	73.263	.418		175.258	.000

the four solutions studied in this paper. Moreover, it improves the performance and increases resistance against stripping.

For further studies, it is recommended to work on the accumulation of snow and deicing method and its effects on the strengths of asphalt layers. It is also appropriate to investigate the effect of these three deicing solutions used in this study on other asphalt strength properties such as fatigue and cracking in asphalt layers at low temperature.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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