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Evaluation of the Effect of Deicing Chemicals on Performance of Airport Concrete Pavement under Freeze-Thaw Cycles

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Abstract

Weather conditions such as rainfall and freeze-thaw cycles affect the pavement performance of airports; therefore, methods such as using de-icing chemicals are considered to maintain the normal condition of the airport runway. In addition to the above factors, de-icing chemicals play an important role in pavement performance and the damage caused to it due to their chemical nature. Therefore, investigating the effect of de-icing chemicals and determining the appropriate material to maintain the airport's pavement is a priority for engineers. In this study, the effect of three de-icing chemicals, sodium chloride, potassium acetate, and ethylene glycol (at concentrations of 23.3%, 49%, and 69.07%, respectively) on skid resistance (The British Pendulum Test (BPT) and The Road Test Machine (RTM)) and the mechanical properties (Compressive Strength Test) of the concrete under Freezing and Thawing Cycle were investigated. The BPT test results showed that sodium chloride resulted in better skid resistance than other chemicals when the number of cycles is more than 100 cycles. This result was also obtained for all cycles in the RTM test. Also, ethylene glycol was not suitable for improving skid resistance based on BPT and RTM tests. Furthermore, the results of the compressive strength of concrete mixtures showed that the de-icing chemicals reduced the compressive strength of concrete mixtures. Based on all the results, sodium chloride had better results than other chemicals.

Keywords

British pendulum tester, Compressive strength, Freezing and thawing cycle, Road test machine, De-icing chemical, airport's pavement

1. Introduction

Freezing-thawing cycles significantly affect airplane landing and take-off safety (Heymsfield et al., 2014). The use of concrete pavements has many advantages, such as reducing environmental impact and reducing maintenance costs compared to asphalt pavements (Besheli et al., 2021; Rezaei et al., 2022). However, the concerning aspect of this pavement is its smooth surface, which has a low skid resistance when a layer of ice is formed on the surface, which ultimately increases the risk of accidents (Han et al., 2020; Zahedipoor et al., 2023).

Skid resistance is one of the most critical road safety issues that has a special place in the operation of airports. The skid resistance is expressed by the coefficient of friction between the tire and the road surface and is measured using various devices at the laboratory or on the road surface (Shi, 2008). Various de-icing chemicals (either in solution or granular) are used to facilitate winter ice and snow removal operations (Sajid et al., 2021). Unfortunately, de-icing chemicals often exacerbate concrete damage caused by the freezing and thawing cycle. Besides creating pressures through osmosis and crystallization, de-icing chemicals increase the degree of concrete saturation and keep concrete pores at or near-maximum fluid saturation, therefore increasing the risk of frost damage (Litvan, 1976). Aggravated damage may be due to chemical interactions between concrete mate-rials and de-icing chemicals. Chemical deterioration of concrete may be caused by washing and decomposition of cement hydration products (Heukamp, 2001), alkali-silica reaction (ASR) (Kawamura, 1994), and rapid concrete carbonation (Kawamura, 1994; Brown and Doerr, 2000; Moradi et al., 2020).

The use of additives in flexible and concrete pavements has become popular in recent years. Various studies have shown that additives have been able to improve most of the engineering properties of pavements (Zarei and Zahedi, 2016; Zahedi et al., 2017a; Zahedi et al., 2017b; Zahedi et al., 2020; Barati et al., 2020; Janmohammadi et al., 2020; Zarei et al., 2020a; Zarei et al., 2020b; Zarei et al., 2020c; Abdi et al., 2021; Abdi Kordani et al., 2021; Rassafi et al., 2021; Sodeyfi et al., 2021; Zarei et al., 2021; Zarei et al., 2022a; Zarei et al., 2022b; Zarei et al., 2022c; Za-rei et al., 2022d; Fatemi et al., 2023; Tabasi et la., 2023a; Tabasi et al., 2023b; Xiong et al., 2023; Hos-seini et al. 2023; Tabasi et al. 2023c; Ziaee et al. 2023; Liu et al. 2023; Wang et al. 2024; Qiu et al. 2024; Yang et al. 2024). With this concept, many chemicals in the world are used as de-icing at airports. Engineers have investigated the effect of these materials to find the best type of de-icing. However, studies on the effect of de-icing chemicals on skid resistance and the mechanical strength of airport pavement have been limited. In critical strategic locations such as airports, the primary purpose is to minimize delays caused by airport closures using de-icing chemicals (Shi, 2008). Therefore, resolving this issue is significant from both a safety and economic point of view. In this study, the effect of de-icing chemicals on the skid resistance of concrete mixtures was investigated using two methods of BPT and RTM. Also, to investigate the effect of de-icing chemicals on pavement strength properties, the compressive strength of the samples was investigated.

The friction between tires and the road surface is responsible for maintaining the vehicle on the road during braking, accelerating, and rotating. Anti-icing, de-icing, and sand materials have been proposed to increase the coefficient of friction to a certain extent (Hall et al., 2009). Many methods have been studied for de-icing. Depending on the type and importance of the pavement, the climate, the economic benefit, and the type of rainfall, the most appropriate de-icing option should be selected and used. Among these, the effective use of de-icing and anti-icing is crucial for maintaining airport safety during winter operations (Bernardin et al., 1996).

Apart from the entrained air in the concrete, a cementitious material's freeze-thaw resistance is deter-mined by its permeability factors, the amount of freezable water, the maximum paste to free surface distance, and the degree of paste saturation (Algin and Gerginci, 2020). Many parameters in the world play a vital role in de-icing for winter maintenance; these include traffic, pavement type, and weather conditions. The amount and type of traffic, along with various factors such as ambient temperature, type of pavement, pavement texture, and pavement conditions, affect road conditions. Weather conditions include air temperature, wind speed and direction, solar radiation, humidity, type and amount of sedimentation, water in the snow, etc. (Muthumani et al., 2014). In addition to the use of chemical de-icing, essential factors depending on the test conditions can affect the properties of concrete pavement, which is mentioned below.

Hazaree et al. demonstrated that the air-entraining additive could be effectively incorporated into the Roller-compacted concrete (RCC) and concluded that the freeze-thaw resistance was considerably enhanced (Hazaree et al., 2011). LaHucik and Roesler show that factors such as different sources of aggregates, different aggregate gradations, compaction methods, and cementitious materials cause significant variations in freeze-thaw resistance even for a fixed cementitious content (LaHucik and Roesler, 2018). Muthumani et al. 2014 reported the laboratory and field effects of de-icing and anti-icing on the concrete pavement. For this purpose, the effect of several chemicals such as betaine, sodium chloride, and potassium acetate on the pavement was investigated. Their results showed that potassium acetate had better skid resistance than betaine, and sodium chloride had better skid resistance than potassium acetate. Therefore, betaine was not recommended as an effective deicer (Muthumani et al., 2014). The effects of de-icing on airport surfaces were investigated by Shi (2008). The results indicated that although de-icing can significantly impact the skid resistance of pavements, overusing it would negatively impact the surfaces (Shi, 2008). Finally, Rodin et al. investigated the skid resistance of concrete pavement with magnesium chloride and calcium chloride chemicals. The results showed that the skid resistance of magnesium chloride was twice that of calcium chloride (Rodin et al., 2019). Previous studies conducted on acetate-based deicers, chloride-based deicers, and agro-based deicers showed that agro-based with high concentrations of either $CaCl_2$ or $MgCl_2$ lead to lower friction coefficients compared to NaCl-based deicers (Fay and Shi, 2011). Using 23.3 ٪ of NaCl de-icing solution increased the friction coefficient of ice pavement by 67.3% compared to when no chemical was used (Nazari and Shi, 2019).

The skid resistance of a pavement surface results from the frictional force resulting from the interaction between the surface of the road and the tire (Li et al., 2021; Sajjad et al., 2021; Liu et al., 2020). Different methods have been used to study the skid resistance of pavements (Zahedipoor et al., 2023; Mahmoudi Nehrani et al., 2021; Yu et al., 2020; Kane and Cerezo, 2015). However, some limitations have led to the use of alternative methods. For example, there are known limitations of BPT, including the method of testing, the shape of their sliders, and the results of inconsistent testing on coarse-textured pavement surfaces (Lee et al., 2005; Purushothaman et al., 1988; Salt, 1977). To overcome the limitations of BPT, an RTM has been developed at the Tarbiat Modares University to measure low-speed pavement friction. In this paper, with a regular laboratory program and by BPT and RTM methods, the skid resistance of concrete pavement containing de-icing chemicals was investigated. Also, a compressive strength test was carried out on the specimens containing de-icing chemicals.

1.1 Research Importance

Standard skid resistance tests are performed for the pavement runway at a speed of 65 or 95 km/h to assess pavement skid resistance for safe aircraft operation. However, when insufficient skid resistance is obtained, measuring high-speed skid resistance alone does not provide sufficient information to determine the true cause of the problem. Therefore, it would be very important to check the low-speed skid resistance (Han et al., 2018). Furthermore, during de-frosting on concrete surfaces, chemicals reduce the freezing temperature of water in the environment. As a result, this matter causes the melting of snow and ice from the pavement surfaces. In addition, water-soluble chemicals cause severe damage to the pavement by penetrating the pavement cracks (Valenza and Scherer, 2006). Therefore, on the one hand, using de-icing chemicals can increase the road surface friction coefficient. However, on the other hand, it reduces the mechanical properties of pavements; hence, simultaneous examination of changes in these engineering properties can give designers and engineers a better understanding. This study attempted to investigate two approaches to overcome this problem:

1. Investigating the effect of the de-icing chemicals on the skid resistance of concrete pavement. In this section, a comparative RTM test was investigated to evaluate the skid resistance of the airport's pavement.
2. Investigating the effect of de-icing materials on the compressive strength of the concrete pavement.

2. Experimental Details and Methodology

2.1 Materials

The cement used was Type II Portland cement with a density of 3.1 g/cm³, and its specifications are presented in Table 1. The water needed to make the specimen was potable water. Limestone coarse and fine aggregates have been obtained from crushed stone mines around Tehran and are presented in Table 2. This study's coarse and fine aggregate gradation follows the ASTM C33 standard (national Iranian code 302) (ASTM C33, 2016). The gradation curve for the coarse and fine aggregate used in this study is shown in Fig. 1.

Table 1 Chemical analysis (% by mass) and physical properties of cement used

Chemical analysis		Physical properties	
Compound	Mass (%)	Test	Value
SiO2	20.1	Surface area (cm2/gr)	3500
CaO	64	Initial setting time (min)	150
Al2O3	5.4	Final setting time (min)	210
Fe2O3	3.9	Compressive strength (kg /cm2) – 2 days	180
MgO	3.4	Compressive strength (kg /cm2) – 3 days	250
SO3	2.3	Compressive strength (kg /cm2) – 7 days	410
K2O	0.7	Compressive strength (kg /cm2) – 28 days	550
Na2O	0.2	Autoclave expansion (%)	0.08

Table 2 Physical properties of natural aggregates

Specifications of aggregates	Standard	Type of aggregates	
		Coarse aggregate	Fine aggregate
Maximum aggregate size (mm)	ASTM C136	19	8
Specific gravity (g/cm³)	ASTM C127	2570	2510
Water saturated surface dry Absorption (%)	ASTM C127	1.25	2.1
Fineness modulus	ASTM C136	-	2.85
Sand equivalent (%)	ASTM D2419	-	75
Los Angeles abrasion	ASTM C121, C535	12.3	-

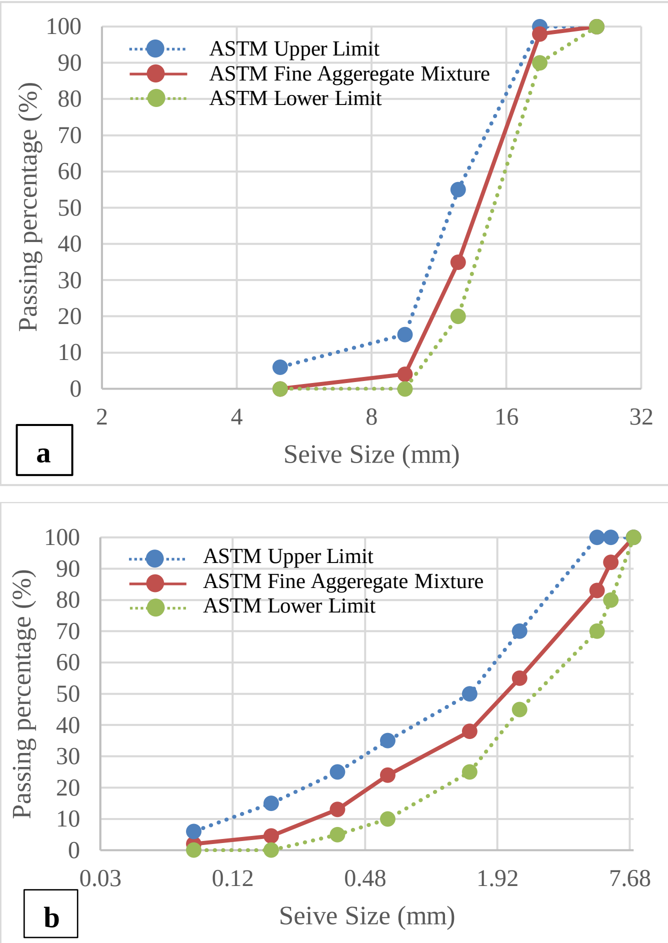

Fig. 1 Gradation of aggregates: a. course, b. fine

2.2 Chemicals additives

In this study, three types of de-icing chemicals, including sodium chloride, potassium acetate, and ethylene glycol, were used to investigate the effects of additives on the compressive and skid resistance of airport concrete pavement.

Sodium chloride, potassium acetate, and ethylene glycol

Sodium Chloride by Chemical Formulas (NaCl) is an ionic compound in which it is composed of equivalent ratios of sodium and chlorine. The production of heat and light accompanies this reaction. For de-icing, if a chemical is used too much, it remains in-soluble and waste. Also, very little use of a chemical may not sufficiently reduce the freezing point. For example, using sodium chloride at a concentration of 23.3% keeps the freezing point at -21.1 °C (Farnam et al., 2015a). This percentage has been used as the optimal ratio in previous studies (Nilssen et al., 2018; Sajid t al., 2021; Claros et al., 2021). Potassium acetate is produced by the chemical reaction of acetic acid with potassium carbonate, which is well soluble in water and alcohol. Farnam et al. 2015b concluded that the freezing temperature reaches -60 °C at a concentration level of 49% (as the optimal percentage); therefore, this percentage was used as the optimal ratio in this study. Ethylene glycol is produced by the reaction of ethylene oxide with water. The solution of ethylene glycol and water in the 1:1 ratio reduces the freezing point to -40 °C. Cordray et al. 1996 concluded that the optimal percentage of ethylene glycol used is between 65 and 70; hence, in this study, ethylene glycol with a solubility of 69.07% was used to investigate the effect of this material on pavement de-icing. Table 3 shows the functional properties of de-icing chemicals.

Table 3 Functional properties of chemicals

Chemical Materials	Sodium Chloride	Potassium Acetate	Ethylene Glycol
Chemical formulas	NaCl	CH_3COOK	$C_2H_6O_2$
Minimum operating temperature	-9^{0}C	-9^{0}C	-12^{0}C
Image of additive			

2.3 Concrete mixing scheme

ACI 211-89 standard was used for mixing design (ACI 211-89, 2009). Three abrasion samples for RTM and BPT tests and three cube samples for compressive strength tests of each mixing design were simultaneously fabricated, cured, and tested in a concrete batch to reduce fabrication errors. Table 4 shows the results of the mixing design using ACI 211-89.

Table 4 Results of the mixing design

Properties of Concrete	Results
Cement grade (kg/m^3)	300
Water to cement ratio (w/c)	0.45
Amount of coarse aggregate consumed (kg/m^3)	864
Amount of sand consumed (kg/m^3)	1040.4
Air content (%)	5.5

Experimental plan

In this study, three types of chemicals were used for comparison with the base state. For this purpose, simple specimens were placed in water to simulate normal conditions during precipitation and without de-icing. To make other specimens and ex-pose the specimens to de-icing, each specimen was placed in separate containers containing chemicals for 72 hours. Also, simple specimens were placed in plain water to be fully saturated for 72 hours. It should be noted that the specimens were cured with water for 28 days prior to exposure to de-icing and water. The 7-days and 28-days compressive strength tests were performed on the specimen with dimensions of 150 × 150 × 150 mm to compare the com-pressive strength. The specimens were placed in a freeze-thaw apparatus after exposure to de-icing. Then, the specimens were removed and cleaned at specific time intervals (8, 16, 32, and 64 hours) and re-inserted into the freeze-thaw apparatus after spraying de-icing and water on the surface of the specimens. Finally, compressive strength and skid resistance tests (BPT and RTM) were performed on the specimens. The overall experimental procedure can be seen in Fig. 2. Also, the experiment design and the number of samples in each experiment are shown in Table 5.

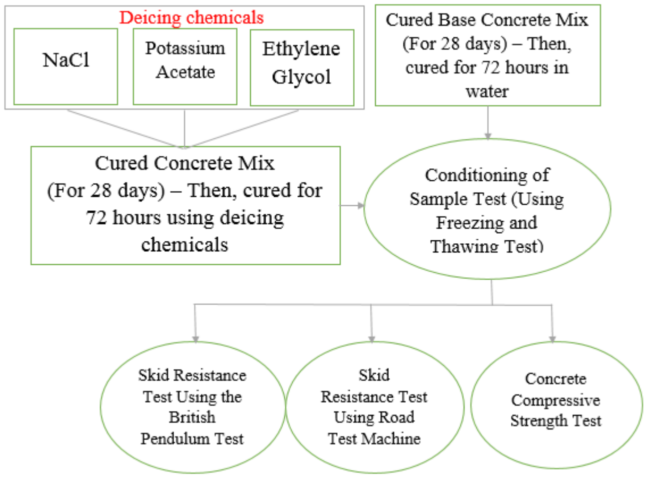

Fig. 2 Chart of the overall experimental procedure

Table 5. Experiment design

Specimen	Chemicals (Percent of concentration)	Exposure	No. of samples	Testing time (cycles or revolution)		
				BPT (Cycle)	RTM (Total Revolution)	Compressive Strength (Cycle)
Concrete Pavement	Distilled water, NaCl (23.3%), Ethylene glycol (69.07%), Potassium acetate (49%)	Freeze-Thaw	24 for each chemical	8, 16, 24, 48, 72, 96, 120, 144, 168, 192, 216, 240, 264, 288, 300	100, 200, 500, 10000, 20000, 40000, 70000, 100000	8, 150, 300

3. Test Method

In this study, the PBT and RTM tests were used to investigate the skid resistance of concrete pavement. Also, a compressive strength test was performed on the specimens. For this purpose, different de-icing chemicals were evaluated to investigate skid resistance and compressive strength.

3.1 Skid Resistance

British Pendulum Test (BPT)

As shown in Fig. 3, the specimens were tested using the BPT (ASTM E303, 2013). To determine the skid resistance of each specimen, five series of BPT were performed, and average data was considered for each output. During the test, the pendulum arm is released from a standard height of H under the influence of its own weight W and is in contact with a small road surface with a dimension of 7.6 cm × 12.5 cm. In this contact, depending on the roughness of the road surface, the pendulum arm loses kinetic energy to W (H-h). The kinetic energy loss is converted to the force of friction, which is then referred to as pavement friction and is expressed by The British Pendulum Number (BPN). The following equation is used to calculate the friction coefficient:

$$\mu = \frac{W \times (H-h)}{D \times P} \qquad (1)$$

Where,
μ = Road surface friction coefficient
W = Arm pendulum weight
H = standard height from test surface to the horizontal position of the pendulum
h = the height obtained after rubber slider contacting the surface
P = Vertical load between the pendulum arm and the test surface
D = Width of rubber slider

Fig. 3 British Pendulum Testing Machine

Road Test Machine (RTM)

There are known limitations to the conventional low-speed skid resistance measuring device, i.e., the BPT. Recently, the RTM has been proposed to overcome limitations and experimentally compare results to measure pavement skid resistance. The RTM is originally inspired by traffic simulators on a smaller scale. The overall view of the device and specimens used is shown in Figs. 4 a-d. The RTM consists of two arms holding steel wheels. The arms are rotated by a speed-controllable transmission system that can achieve a maximum speed of 30 rpm. Two springs placed on each wheel control the force exerted by the wheel, which may be detected using a weighing sensor beneath the wheel. The loading system, illustrated in Fig. 4d, can apply a maximum load of 450 kg for each wheel. The pavement samples are shaped like a square toroid section (Fig. 4a). The sample mold is illustrated in Fig. 4d. Eight samples are placed and fixed in the device in each test run to undergo abrasion induced by wheel passage. In this experiment, the traffic factor is measured by the number of passing wheels, and the wheels are rotated around the axle at a speed of 10 rpm. Wheels weight is 5kN which can vary for airport conditions. The usual temperature for this test is 10 °C. To calculate the skid resistance of the samples, first, the samples were loaded in the revolution numbers of 100, 200, 500, 1000, 2000, 5000, 10000, 20000, 40000, 70000, and 100000; then, the average depth of the abrasion groove was calculated using a high-precision depth gauge (After cleaning the groove surface). Finally, the RTM was calculated using the following formula:

$$RTM = \frac{1}{D} \tag{2}$$

Where D is the average skid depth in meters, and RTM is the skid resistance in inverse meters.

The advantage of this test over the BPT is that the loading is more like reality; therefore, using this device will have better results. Fig. 4 shows the RTM and the specimen tested by the RTM.

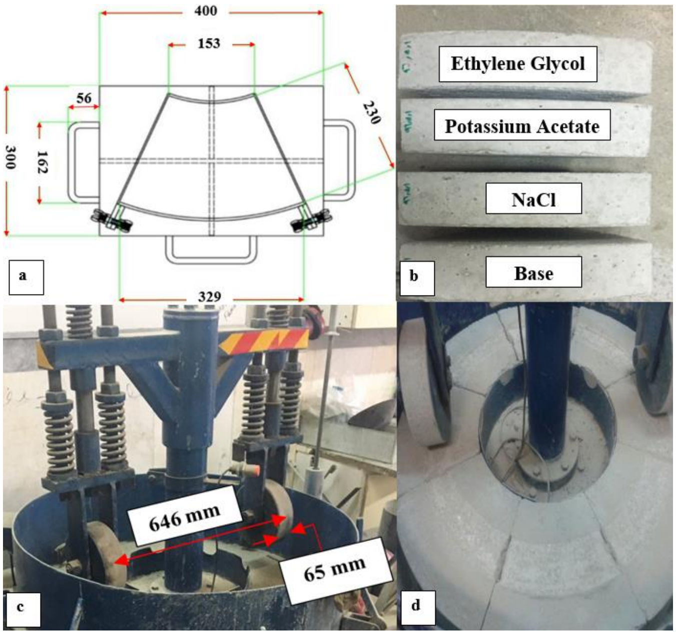

Fig. 4 Specimen used in the RTM

3.2 Freeze-Thaw Test

The ASTM C666 standard provides two methods for determining concrete's resistance to rapidly repeated freezing and thawing cycles (ASTM C666, 2008):

Method A) Rapid freezing and thawing in water; and

Method B) Rapid freezing in air and thawing in water.

Both methods' freezing and thawing cycles are such that the temperature fluctuates from -17.8 °C to +4.4 °C. Each cycle time is between 2 and 5 hours. For methods A and B, less than 25% and 20% of the time are used for the thawing period, respectively. At the end of the freezing period, the specimen's central temperature should be -17.8±2 °C. At the end of the thawing period, the temperature should be 4.4±2 °C. The temperature should not be less than -19 °C and not more than +6 °C in the first experiment. The temperature difference between the center and the surface of the specimen should not exceed 28 °C. Also, the transition period between the freezing and thawing cycles should not exceed 10 minutes. Testing on the specimens will continue for 300 cycles until the dynamic elastic modulus reaches 60% of the initial modulus. In this study, method B was used to apply freezing and thawing cycles. Fig. 5 shows the AT4001-250 freezing-thawing cycle machine.

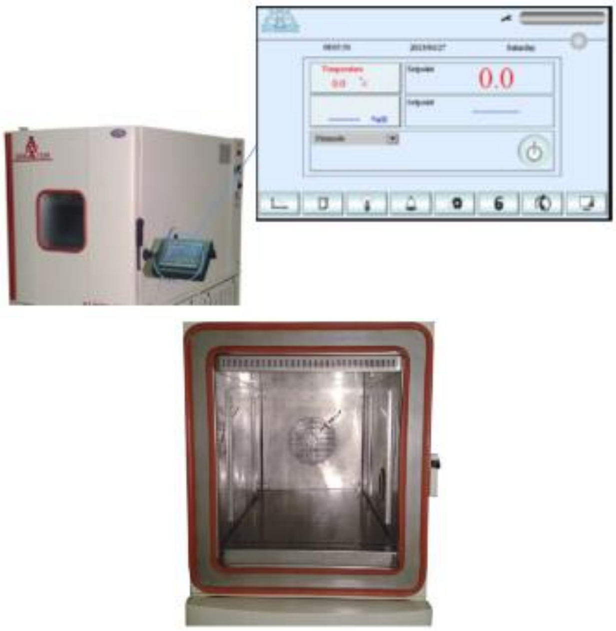

Fig. 5 AT4001-250 freezing-thawing cycle machine

3.3 Compressive Strength Test

A total of 24 cylindrical specimens with dimensions of 150 mm diameter × 300 mm height and a total of 60 cubic specimens with dimensions of 150 mm × 150 mm × 150 mm × 150 mm are prepared for testing. For each type of mixture, 3 repetitions were considered. The compressive strength tester is calibrated according to the ASTM C39 standard (ASTM C39, 2001).

4. Results and Discussion

4.1 Skid Resistance Test Results

British Pendulum Test

Fig. 6 shows the trend of changes in skid resistance of the tested specimens during the freezing and thawing cycle. In cycles less than 100, deterioration consisted primarily in surface scaling off the cementitious matrix surface (sand + paste). However, the share of coarse aggregate is less (Del Bosque et al., 2020). In this situation, the matrix detachment separated the aggregate and thinned the aggregate/paste ITZ until the aggregate loosened. In this situation, the matrix detachment separated the aggregate and thinned the aggregate/paste ITZ until the aggregate loosened. However, due to the presence of de-icing materials in the water, the samples cured in these conditions showed less resistance than the base samples. At cycles greater than 100, the simultaneous effect of cycles and de-icing materials resulted in further damage to the concrete surface (participation of coarse aggregates in the sample skid resistance). Finally, the skid resistance of the concrete surface showed more numbers than the base sample (Del Bosque et al., 2020). The results of skid resistance showed that the specimen containing ethylene glycol with a BPN of 31 in 300 cycles has the lowest skid resistance compared to other specimens throughout the cycle. Also, when the number of cycles is greater than 100, the Sodium chloride specimen had better performance against skid resistance.

Fig. 7 shows the skid resistance of the specimens tested in cycle 300. The skid resistance number was obtained by performing all experiments in different cycles. The results showed that the specimen containing sodium chloride had the highest skid resistance. In contrast, the specimen containing ethylene glycol had the lowest skid resistance. As shown in Fig.. 8, the results of skid resistance loss showed that the specimen containing sodium chloride and potassium acetate (38% and 42%, respectively) had the lowest skid strength loss. However, the specimen containing ethylene glycol with 53% had the highest skid resistance loss. Hence, it seems that ethylene glycol is not a good material compared to other de-icing materials for use in winter maintenance operations on concrete pavement. Liu et al. (2003) reported BPN values for PCC of 32 in wet conditions and 67 in dry conditions (Liu et al., 2003). Houle (2008) tested three basic conditions for concrete pavement and recorded values of 29, 74, and 97 for icy, wet, and dry conditions, respectively (Houle, 2008). Table 6 shows the statistical analysis of the results, including standard deviation (SD) and coefficient of variance (COV).

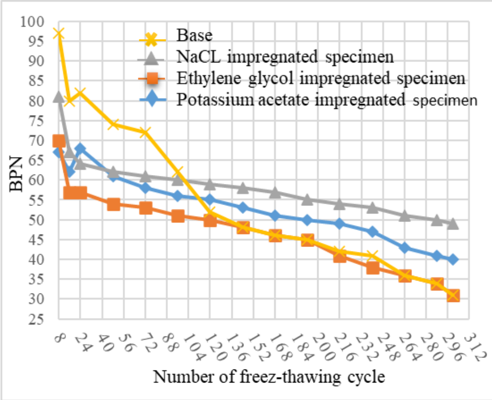

Fig. 6 Trend of changes in skid resistance of tested specimens

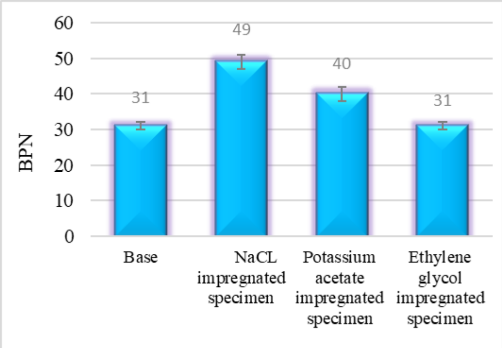

Fig. 7 Skid resistance of the specimens tested in cycle 300

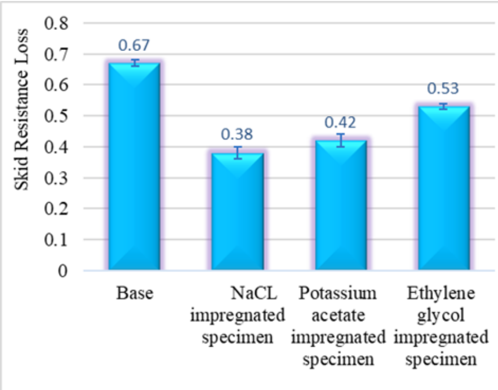

Fig. 8 Skid resistance loss of the specimens tested in cycle 300

Table 6 Statistical analysis for the results

Mixtures	BPN			Skid Resistance Loss		
	Ave.	SD.	COV.	Ave.	SD.	COV.
Base	31	0.817	0.026	0.67	0.008	0.012
NaCl	49	1.633	0.033	0.38	0.016	0.043
Potassium acetate	40	1.633	0.041	0.42	0.016	0.039
Ethylene glycol	31	0.817	0.026	0.53	0.008	0.015

Road Test Machine (RTM)

The skid resistance number of each specimen was obtained separately after the accelerated wear process by the rotating device. Fig. 9 shows the trend of changes in skid resistance of the tested specimens. The results of the skid resistance of the specimen tested by RTM showed that the specimen containing sodium chloride had better skid resistance than the other specimen. Also, the specimen containing ethylene glycol had the lowest skid resistance of the other specimens.

Fig. 10 shows the skid resistance of the specimens at 100,000 revolutions. The results showed that the mixture containing sodium chloride with friction number 0.63 had the highest skid resistance. Also, ethylene glycol with a friction value of 0.46 did not affect the skid resistance of the concrete. Fig. 11 shows the Skid resistance loss of the specimens at 100,000 revolutions. The results of skid resistance loss showed that sodium chloride with 18% had the lowest skid resistance loss among the specimens. In contrast, the highest skid resistance loss was related to the base state. The specimen containing ethylene glycol with 26% had the highest skid resistance loss. Comparison of RTM and BPT results showed that both experiments had similar results. Table 7 shows the statistical analysis of the results, including standard deviation (SD) and coefficient of variance (COV).

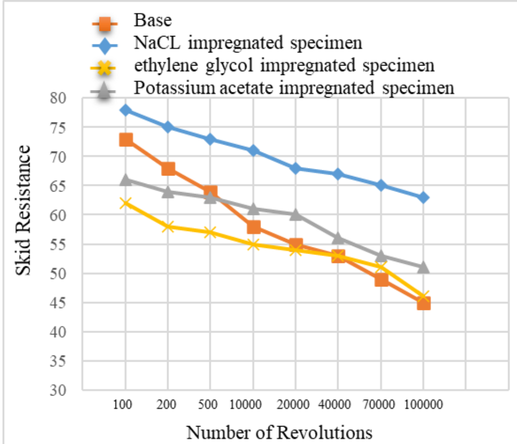

Fig. 9 Trend of changes in skid resistance of the tested specimens

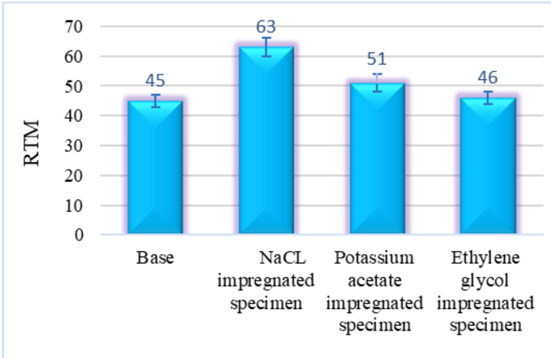

Fig. 10 Skid resistance of the specimens at 100,000 rpm

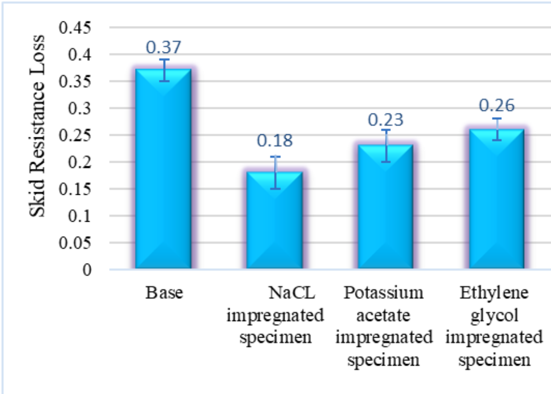

Fig. 11 Skid resistance loss of the specimens at 100,000 rpm

According to the results, it was found that sodium chloride had better skid resistance for use in winter pavement maintenance. Subsequently, potassium acetate was ranked second in all tests. However, several factors influence the choice of de-icing, such as surface temperature, air humidity, saturation temperature, exposure to sunlight, and the rate and type of sediment produced by de-icing. For this reason, although sodium chloride had better results in all experiments, it is better to consider all the above in its selection (Muthumani et al., 2014). Previous studies have shown that calcium magnesium acetate and magnesium chloride are more useful for winter pavement maintenance at lower temperatures. However, they are more expensive and more sensitive than other materials; therefore, using sodium chloride as a de-icing chemical can be economically justified.

As mentioned, sodium chloride cannot be used in airport pavement despite its lower cost and easier application because it has a significant effect on the stripping phenomenon and has a detrimental effect on flight bands. However, using these materials at the appropriate temperature range can significantly reduce pavement winter maintenance costs. Therefore, having a proper plan for ice and snow control operations will lead to better choices. As a result, accelerating defrosting operations and reducing costs will result (Fritzsche, 1989).

Table 7 Statistical analysis for the results

Mixtures	RTM			Skid Resistance Loss		
	Ave.	SD.	COV.	Ave.	SD.	COV.
Base	45	1.633	0.036	0.37	0.0163	0.044
NaCl	63	2.450	0.039	0.18	0.0245	0.136
Potassium acetate	51	2.450	0.048	0.23	0.0245	0.107
Ethylene glycol	46	1.633	0.036	0.26	0.0163	0.063

4.2 Results of compressive strength test

The results of the 7 and 28-days compressive strengths for the cubic and cylindrical specimens for all four concrete mixtures are given in Fig. 12 and Table 8. The compressive strength test results showed that the specimen containing de-icing mate-rials at the ages of 7 and 28 days resulted in a decrease in the strength of the concrete mixture. The results showed that potassium acetate had the most decrease in compressive strength compared to the base mixture. Comparison of the effect of the mixture containing ethylene glycol and sodium chloride showed that the performance of the two mixtures was similar. The reduction of compressive strength in concrete mix can be studied from two perspectives; first, the freeze-thaw cycles; second, the effect of de-icing chemicals. The obtained results were a combination of both conditions since the resistance of the samples was calculated after applying both conditions. Previous studies showed that the deterioration of the concrete mix was affected by the simultaneous effect of the freezing-thawing cycles and the de-icing chemicals. Based on the results, the development of pore pressure during freezing-thawing cycles in the presence of de-icing chemicals was partly attributed to the effect of solution motion or ice formation (Amini, B., & Tehrani, 2011; Panesar and Chidiac 2009). Haselbach et al. investigated the effect of calcium chloride deicer on the compressive strength of concrete mix at high and low porosity. The results showed that the compressive strength of the samples was dependent on the porosity as well as calcium chloride deicer; however, with increasing porosity of the samples, the compressive strength was affected by the porosity rather than calcium chloride deicer (Haselbach et al., 2021).

The compressive strength in the loading cycle (8, 150, and 300) and in the freezing and thawing experiments are given in Fig. 13 and Table 9. As shown in Fig. 13, the most significant decrease was observed in the freezing and thawing cycles and for the concrete mixture containing potassium acetate. Also, the result showed that the concrete mixture containing ethylene glycol had good resistance to freezing conditions (In cycles 150 and 300). This result (re-duction of compressive strength of sample containing sodium chloride compared to the sample containing ethylene glycol) is justified by the corrosion of the concrete by sodium chloride. Therefore, it is necessary to consider the concrete mixing design in order to prevent the decrease of resistance. Wang et al. (2006) investigated the destructive effects of de-icing chemicals on concrete materials. The results showed that sodium chloride and potassium acetate partially reduced the compressive strength. Also, they found that potassium ions had more penetration than sodium ions. Therefore, the damage of concrete pavement by potassium acetate was greater than sodium chloride (Wang et al., 2006). Also, ethylene glycol is compounded by the fact that the material decomposes very slowly at temperatures below freezing temperature. Therefore, the aerobic microbes are inactive and are diluted very slowly when groundwater and surface water are frozen. This leads to pulses of relatively high chemical levels during thaws (Current De-icing Practices and Alternative, 2018). As mentioned, different methods have been proposed to melt the ice on airport pavements. Although de-icing chemical causes ice melting, it may affect other pavement properties such as Compressive strength. In this study, it was observed that de-icing chemicals reduced compressive strength. Therefore, the reinforced concrete mixture is recommended with additives in different ways for using de-icing chemicals. By comparing these results with the results shown in Figs. 12 and 13, it can be concluded that sodium chloride has better compressive strength.

Table 8 Statistical analysis for the results

Mixtures	Compressive strength											
	Cubic - 7 days			Cubic - 28 days			Cylindrical – 7 days			Cylindrical – 28 days		
	Ave.	SD.	COV.	Ave.	SD.	COV.						
Base	21	0.408	0.019	28	0.817	0.029	17	0.817	0.048	23	0.817	0.036
NaCl	19	0.817	0.043	28	0.817	0.036	16	0.817	0.051	22	0.817	0.037
Potassium acetate	18	0.817	0.045	22.5	0.817	0.036	12	0.817	0.068	21.5	0.408	0.019
Ethylene glycol	18	0.817	0.045	27	0.408	0.015	15	0.817	0.054	18	0.817	0.045

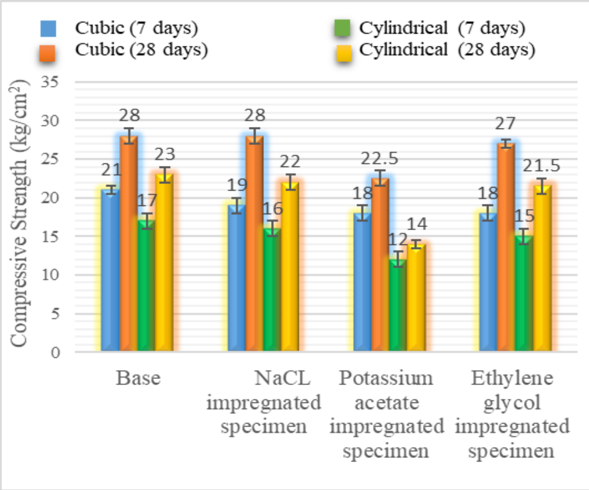

Fig. 12 Compressive strength of the test specimens

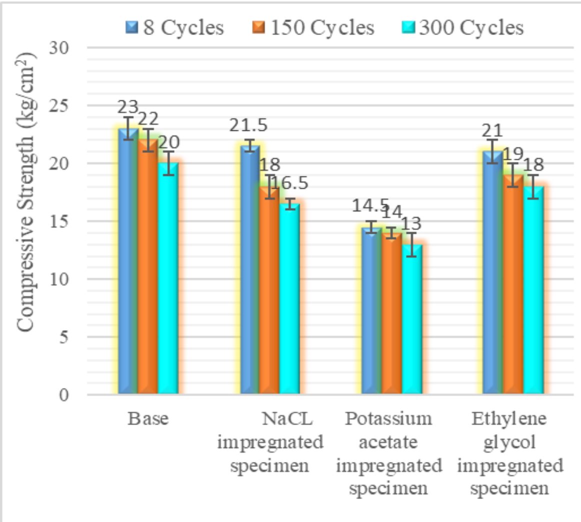

Fig. 13 Compressive strength of the test specimens in different cycles (8, 150 and 300)

Table 9 Statistical analysis for the results

Mixtures	Compressive strength		
	8 Cycles		
	Ave.	SD.	COV.
Base	23	0.817	0.0355
NaCl	21.5	0.408	0.0190
Potassium acetate	14.5	0.408	0.0282
Ethylene glycol	21	0.817	0.0389
	150 Cycles		
Base	22	0817	0.0371
NaCl	18	0.817	0.0454
Potassium acetate	14	0.408	0.0292
Ethylene glycol	19	0.817	0.0430
	300 Cycles		
Base	20	0.817	0.0408
NaCl	16.5	0.408	0.0247
Potassium acetate	13	0.817	0.0628
Ethylene glycol	18	0.817	0.0454

5. Conclusions

This paper tested three types of freezing agents (sodium chloride, potassium acetate, and ethylene glycol) at different percentages. To evaluate the effect of these three materials, the specimens were placed in a chemical container for 72 hours to be completely impregnated. Compressive strength tests were performed on the specimens to investigate the compressive strength of specimens. Finally, to investigate the specimens' skid resistance, they were first cured using a freezing and thawing cycle and then tested using BPT and RTM methods. The results of the experiments are presented below:

- Comparing the mixtures containing de-icing with the base specimen showed that the de-icing reduced the compressive strength of the concrete mixtures. The highest reductions were 29, 14, and 9.5%, respectively, for mixtures containing potassium acetate, ethylene glycol, and sodium chloride.
- The compressive strength results in the freezing and thawing cycles of 8, 150, and 300 showed that the frost resistance reduction for the mixture containing sodium chloride was 6.5%, 18, and 17.5%, respectively. This reduction was 37%, 36%, and 35% for samples containing ethylene glycol, and 8.5%, 13.5%, and 10% for samples containing potassium acetate, respectively.
- The results of skid resistance during the freezing and thawing cycle using the BPT showed that the specimen containing ethylene glycol with BPN 31 had lower skid resistance compared to the other specimen. Also, the study of changes during the freezing and thawing cycle showed that the specimen containing sodium chloride had better performance (about 49) than the base state.
- The skid resistance results of the BPT showed that the specimens containing sodium chloride and potassium acetate had a 38% and 42% reduction in skid resistance, respectively.
- The results of the skid resistance of the specimen tested by RTM showed that the specimen containing sodium chloride with RTM 63 had better skid resistance than the other specimen in the number of 100,000 revolutions. Also, the sample containing ethylene glycol had the lowest skid resistance com-pared to the other samples.
- According to the results, it is better to introduce sodium chloride as a suitable alternative due to better skid resistance (BPT and RTM tests), less reduction in compressive strength (7 and 28 days), and adequate compressive strength in all freeze-thaw cycles.

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