their weight losses are reaching failure threshold earlier in a saline solution compared with those samples in fresh water (Sun et al. 2002).

As shown in Figure 3b, the amount of concrete compressive strength decreased moving from freshwater to 10% saline solution and increased again from 10% to 20% saline solution to some extent. However, as shown in this figure, the amount of mean for all three boxplots are equal to some extent. Plus, after increasing the amount of saline solution from 10% to 20%, it has been seen that the amount of concrete peeling was decreased. The interesting factor to take notice of is that this phenomenon can occur as a result of the reached its optimum level at a point between 10 and 20 percent of NaCl. More samples and studies are needed to find out more about the phenomenon. Moreover, it is evident that the 10% boxplot did not follow the same trend as the 20% boxplot followed.

According to these results shown in figures 3a, 3c, and 3d, samples in contact with saline solution had less compressive strength than that those only in contact with air (in the absence of solution) in their freezing and thawing process. Likewise, statistical analysis and Duncan's Multiple Range Test (DMRT) showed that there was a significant difference between 10% of saline solution and 20% of saline solution (p-value < 0.05).

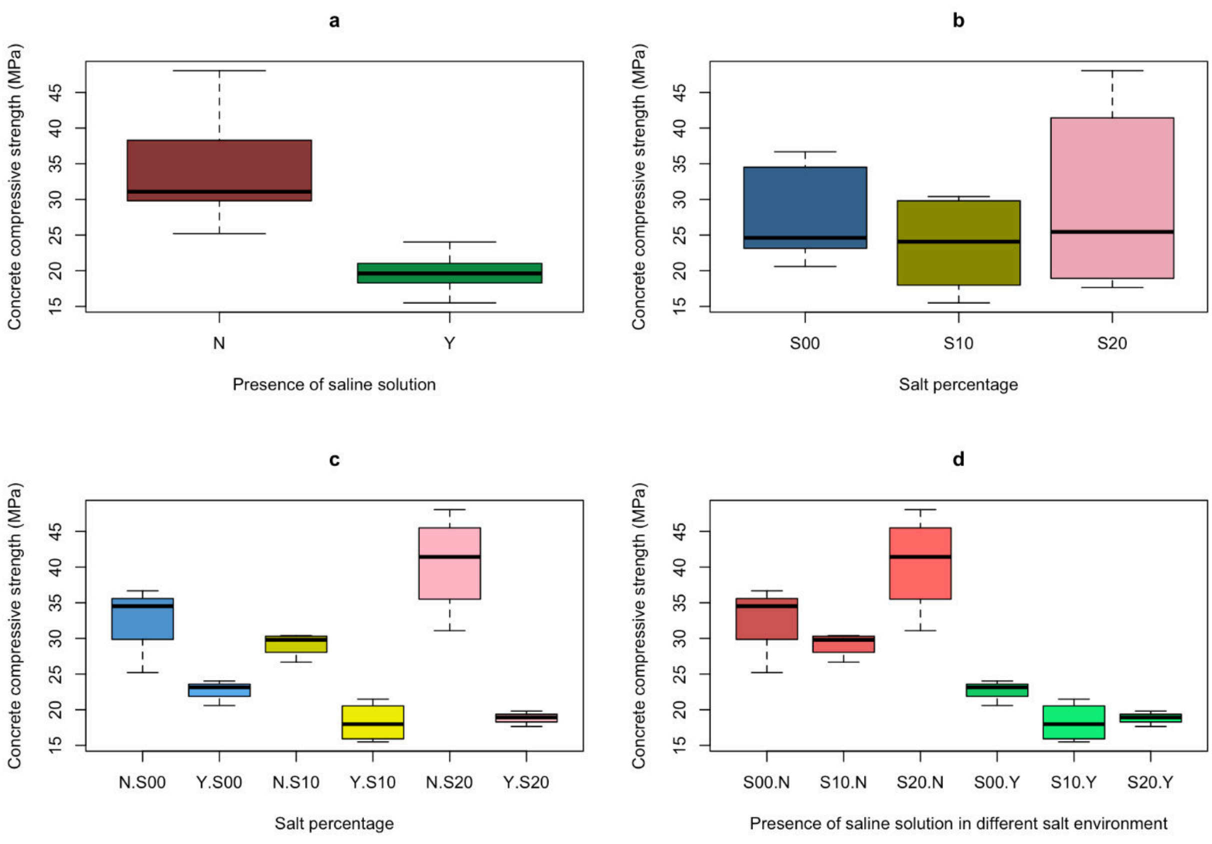

Figure 3. The impact of de-icing salt (NaCl) on the compressive strength of concrete

Duncan plots. The Duncan analysis shown in Figure 4 rejects the equality of mean compressive strength values with an alpha value of 0.05 indicating a confidence level of 0.95 for specimens in presence or absence of solution. Similarly, the mean values observed for 10% and 20% salt, S20-S10 have meaningful differences.

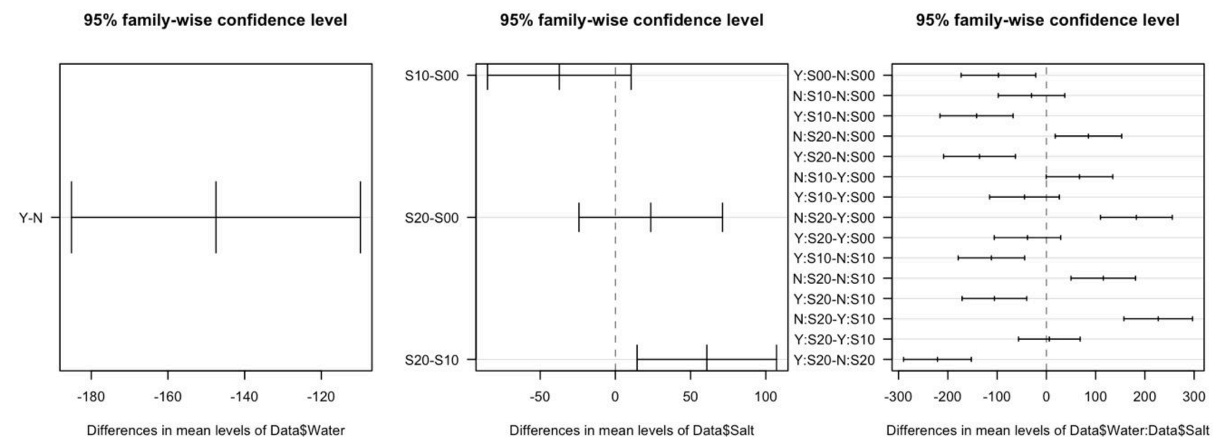

Figure 4. Concrete compressive strength Duncan plots.

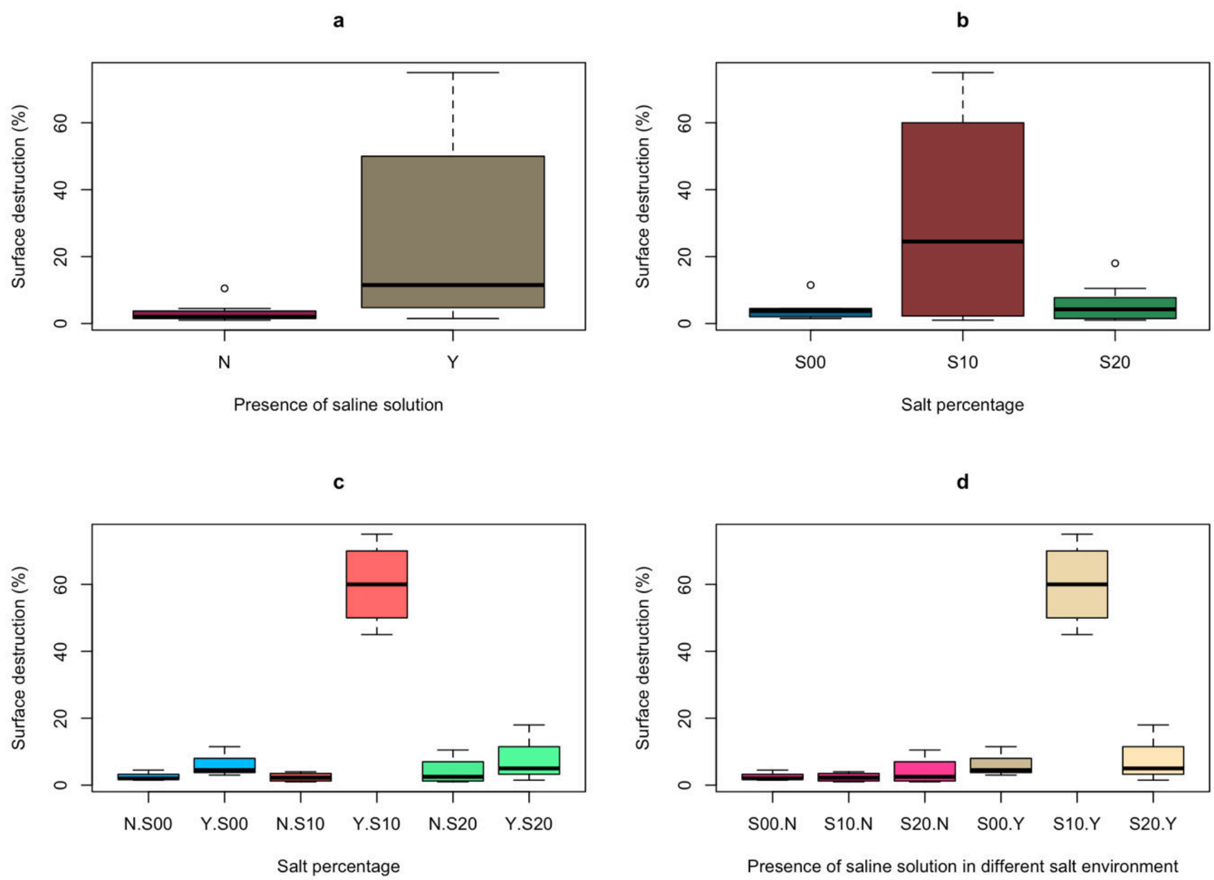

Figure 5. The impact of de-icing salt (NaCl) on the concrete surface destruction.

Destruction and weight losses. Figure 5 exhibits weight losses of concrete specimens subjected to freeze-thaw cycling in freshwater or NaCl solution. Figure 5a shows the weight losses and concrete surface destruction increased for the concrete exposed in freshwater or saline solution subjected to freeze-thaw cycling. Figure 5b refers to the results of the freeze-thaw cycling in different saline solution environment. The most outstanding and highlighted point in figure 5a, 5c, and 5d that should be taken into consideration would be the fact that from all of these boxplots, the most prominent and influential point is when concretes is in saline solution with 10% of NaCl by weight. Likewise, this point has been seen and obtained from the laboratory examination's empirical experiments (Figure 6). The amount of destruction and weight losses in concrete exposed with 10% of saline solution is significantly higher than in other samples. Plus, P-value and Duncan's test have proven these observations.

Figure 6a presents a sample exposed to 80 freeze-and-thaw cycles in presence of potable water without salt. Figure 6b presents the most damaged sample as a result of exposure to 10% salt. The highest peeling damage is apparent on the surface of this specimen. Figure 6c shows a sample exposed to 20% salt indicating less damage than prior sample. Finally, figure 6d exhibits a comparison between damaged specimens exposed to – from left to right - 0%, 10%, and 20% salt. These visual observations confirm statistical results and diagrams in figure 5.

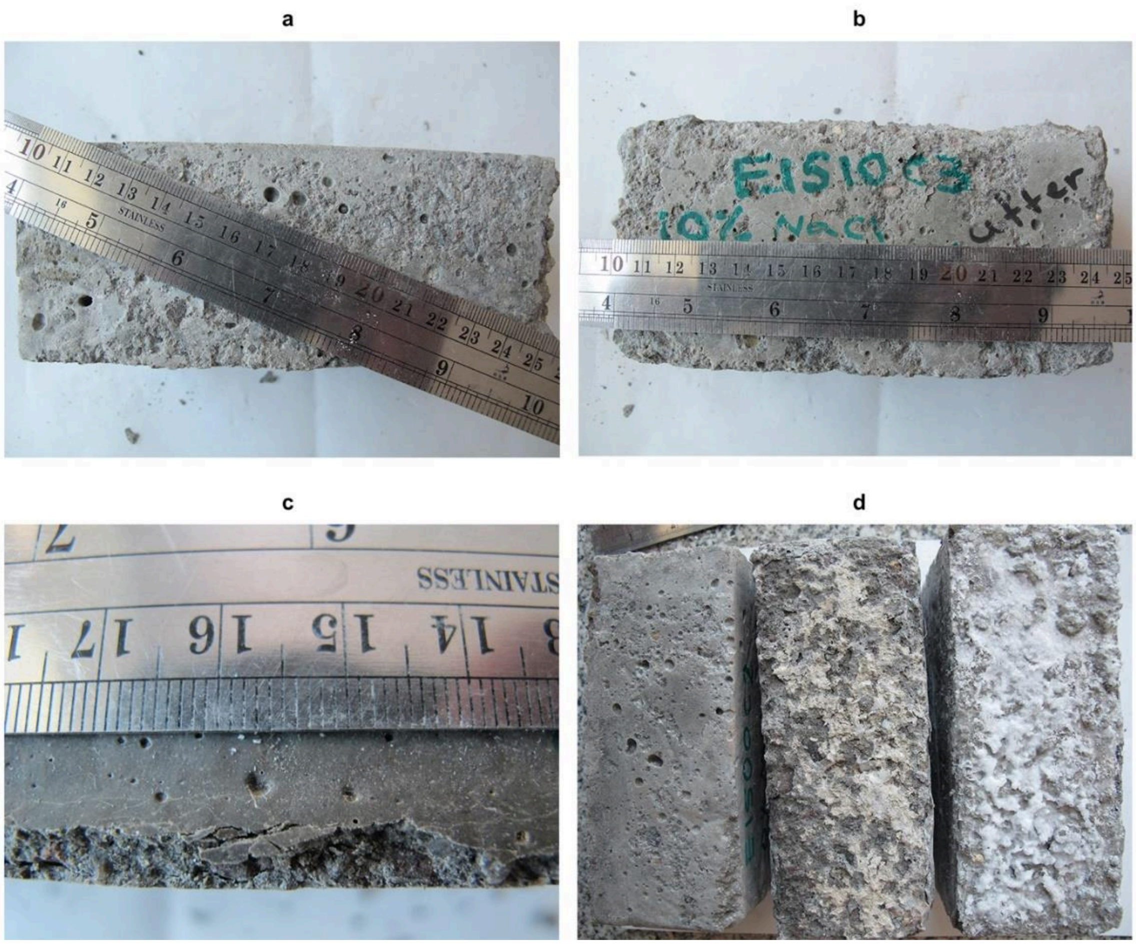

Figure 6. Concrete surface destruction and weight losses during the freeze-thaw cycling.

CONCLUSION

This paper confirms the existing knowledge on the influence of freezing and thawing on degradation of concrete samples. Experimental investigations provided quantitative measures to understand the evolution of concrete degradation due to environmental changes, such as saline contents. Further, data analyses reveal the reliability of experimental results considering the limited number of specimens in experimental studies. Following conclusions can be extracted from this work:

- Results show that the concrete samples subjected to freezing and thawing destruct and lose weight more severely in the presence of de-icing salt solution with 10% NaCl by weight than those in the presence of freshwater.
- However, as shown by the data and empirical samples in the laboratory, the amount of peeling and destruction decreases with the rising of saline solution percentage from 10% to 20% to some extent.
- Likewise, from the data, P-value<0.05, and Duncan's test, the most noticeable (prominent) factor affecting the destruction and weight losses the most would be the presence of saline solution with 10% of NaCl by weight.
- Additionally, it should be noted that the presence of a de-icing solution increases and escalates the weight losses and compressive strength at 28-day age.

Concluding remarks warrant further studies to include larger number of specimens exposed to larger number of saline conditions to enhance the reliability of results.

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A Quantitative Investigation of the Durability of Asphalt Pavement Materials Using Experimental Freeze-and-Thaw Weathering Data

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ABSTRACT

This paper highlights trends in asphalt concrete damages due to freeze-and-thaw cycles. Various independent parameters, such as thermal and chemical conditions, and their combined actions contribute to these damages and reduce the service life of asphalt pavements. The existing literature is rich on the effect of freeze-and-thaw cycles in presence of deicing chemicals. Further, the assessment of damages in respect to physical, chemical, and mechanical characteristics of asphalt pavement materials has gained extensive attention in academic research and practice projects. The presented investigation examines the observed trends of damages due to various material properties and environmental conditions and aims to offer quantifiable performance measures to assess the sustainability and resilience of asphalt materials in response to severe conditions. Essential properties of asphalt materials include permeability, the porosity of aggregates, presence of chemicals or salts, water flow and pressure, chemical stability of aggregates, and applied cycles of freezing and thawing. Reported measures typically include weight loss and strength reduction. Conclusions highlight participating factors in determining the service life of asphalt pavements and associated costs and environmental footprints of transportation infrastructure.

INTRODUCTION

Sustainability and resilience of infrastructure rely on various societal, environmental and technical parameters (Tehrani 2017; Nelson and Tehrani 2018). Essential parameters for horizontal infrastructure like transportation systems involve optimization of resources and reduction of environmental footprints on natural world (Tehrani 2019). Application of durable, lightweight and recycled materials are common in pavement applications to achieve such performance measures through reduction of input energy and greenhouse gas emissions (Tehrani 2015; Tehrani and Dadkhah 2018; Nazari et al 2019; Tehrani et al. 2019). Assessing the effectiveness of these materials on the durability and service life of pavements require understanding their performance in response to environmental exposures (Tehrani 2020a; Tehrani 2020b).

Asphalt pavements are vulnerable to various independent parameters throughout their lifecycle. Thermal and chemical conditions and their interactions, like the presence of deicing agents during freeze-and-thaw cycles, reduce the service life of the pavement and cause damages in cold regions. Accumulation of moisture and water in wet regions, penetration of water into voids, and volume changes during freezing, presence of deicing chemicals, and water flow contribute to the degradation of asphalt. In addition, the durability of a pavement depends on the physical and mechanical properties of both aggregate and bituminous contents of asphalt mixtures and their sensitivity to water penetration, thermal conditions, and chemical agents (Feng et al. 2010). The interaction of various parameters complicates the design process and often results in over-estimation of the service life of the pavement (Guo et al. 2018). This paper highlights selected trends in asphalt damages due to freeze-and-thaw cycles using statistical analysis of existing experimental data on tensile strength and weight loss.

DEGRADATIONS OF ASPHALT CONCRETE

Essential properties of asphalt materials include permeability, the porosity of mixture, presence of chemicals or salts, water flow and pressure, chemical stability of aggregates, and applied cycles of freezing and thawing.

Permeability and Porosity. Permeability determines the penetration of water into asphalt that may cause damages due to volume changes during freeze-and-thaw cycles. The quantity and size of voids influence this behavior, as water accumulated in smaller voids tend to freeze at lower temperatures and causes less pressure during freezing. A finer gradation of aggregates typically contributes to reducing of permeability and porosity of asphalt mixtures (Amini and Sharif Tehrani 2012). As the freezing cycles increase, more porosity is created in the asphalt and more moisture enters the sample. The shape and size of pores also interact with this process, which finally results in the reduction of the adhesion between asphalt and aggregates and degrades the performance of asphalt mixtures (Gong et al. 2018).

Deicing Agents. The main function of these agents is lowering the freezing temperature. However, these agents are also responsible for striping action in asphalt mixtures (Lovqvist 2019). Experimental investigations have correlated the weight loss in asphalt and salt content during freeze-thaw-cycles (Feng et al. 2010; Amini and Sharif Tehrani 2012; Hassan et al. 2002). Hence, the salt concentration is a key parameter in determining asphalt damages and their trends throughout time with maximum damages reported at 1 to 2 percent contents (Hassan et al. 2002) with smaller sensitivity at contents less than 3 percent (Feng et al. 2010).

Water Flow. The flow of water caused by either road surface slope or tire movements on the surface breaks down the connection between ice crystals and slows down the freezing (Amini and Sharif Tehrani 2012). However, the additional hydraulic pressure due to such flow may cause additional strains and stresses within the asphalt layer. The presence of voids and their interconnectedness as well as the gradation of aggregates influence the water flow (Lovqvist 2019).

Chemical Properties of Aggregates. Alkali aggregates have greater resistance than acidic aggregates against deicing agents and freeze-and-thaw cycles (Hassan et al. 2002). Freeze-thaw and deicers also appear to influence the viscosity of bituminous materials (Hassan et al. 2002). Although deicers, decrease frost damage, they may also influence the bonding capacity of bituminous contents and cause stripping (Lovqvist 2019).

METHODOLOGY

This paper utilizes existing experimental studies to establish a relationship between various parameters and the expected performance of asphalt mixtures. Experimental data include aggregate properties and freeze-thaw characteristics. Comparison of normalized data and statistical analysis facilitate identification of parameters that tend to shorten the service life of asphalt pavements.

Assessing mechanical properties. Table 1 provides a summary of selected experimental studies on the influence of freeze-and-thaw cycles on the strength of asphalt mixtures. These studies involve a variety of aggregates and various concentrations of salt and deicing agents.

Table 1. Selected experimental studies on the performance of asphalt mixtures exposed to freeze-and-thaw cycles.

No.	Reference	Specimen*	Standard	Freeze-and-thaw conditions	Water condition
1	Feng et al. (2010)	AC-16	ASTM D6927	8 hrs of 20°c and 4 hrs of 60°c	Distilled water
2	Feng et al. (2010)	AC-16	ASTM D6927	8 hrs of 20°c and 4 hrs of 60°c	3% salty
3	Feng et al. (2010)	AM-16	ASTM D6927	8 hrs of 20°c and 4 hrs of 60°c	Distilled
4	Feng et al. (2010)	AM-16	ASTM D6927	8 hrs of 20°c and 4 hrs of 60°c	3% salt
5	Feng et al. (2010)	AM-16	ASTM D6927	8 hrs of 20°c and 4 hrs of 60°c	6% salt
6	Feng et al. (2010)	OGFC-19	ASTM D6927	8 hrs of 20°c and 4 hrs of 60°c	Distilled
7	Feng et al. (2010)	OGFC-19	ASTM D6927	8 hrs of 20°c and 4 hrs of 60°c	3% salt
8	Tang et al. (2014)	Basalt below 16 mm	ASTM D6927	16±0.5 hrs in -18° and 8±0.5hrs in 60° water and 2hrs in 25° air	Distilled
9	Tang et al. (2014)	Basalt below 16 mm	ASTM D6927	16±0.5 hrs in -18° and 8±0.5 hrs in 60° water and 2hrs in 25° air	Salty
10	Feng et al. (2009)	AC-16 with hydrated lime	ASTM D6927	8 hrs of 20°c and 4 hrs of 60°c	Distilled
11	Feng et al. (2009 (	AM-16 with hydrated lime	ASTM D6927	8 hrs of 20°c and 4 hrs of 60°c	Distilled
12	Feng et al. (2009 (	OGFC-19 with hydrated lime	ASTM D6927	8 hrs of 20°c and 4 hrs of 60°c	Distilled

* AC-16: A dense-graded asphalt mixture with 6% air voids and 16 mm nominal maximum aggregate sizes
AM-16: A semi-open-graded asphalt mixture with about 12% air voids.
OGFC-19: An open-graded friction courses with 18% air voids.

Trends of asphalt Damages. Experimental studies reveal that asphalt degradation occurs in two cycles. First, the volume change of water due to early cycles of freeze-and-thaw causes cracking, stripping, and reduction of tensile strength; and second, following cycles of freeze-and-thaw cycles cause weight loss in cracked asphalt mixtures (Feng et al. 2010). Further, experimental studies on various aggregates indicate that mixtures with lower permeability experience more strength loss due to freeze-and-thaw cycles (Feng et al. 2010). Moreover, specimens exposed to distilled water show a sudden strength loss due to the first cycles of freeze-and-thaw but have less loss per cycle in the following cycles. In comparison, specimens exposed to salt have less loss in preliminary cycles and more losses in following cycles, showing more long-term vulnerability than those exposed to distilled water (Feng et al. 2010). Increasing the porosity in the mixture causes more strength loss due to freeze-and-thaw cycles. However, open-graded mixtures that facilitate water flow show less vulnerability to these cycles (Feng et al. 2010). The gradation of aggregates controls both permeability and water flow in asphalt mixtures. Finer aggregates typically result in denser mixtures with less water penetrating or flowing within the body of the asphalt.

RESULTS

Reported measures of asphalt mixtures typically include weight loss and strength reduction due to freeze-and-thaw cycles.

Tensile Strength. Figure 1 shows the reduction trends of tensile strength over time for various specimens containing different aggregates and different testing environments, as referenced in Table 1. The red curves in Figure 1 represent the normal distribution diagram in each period of freeze-thaw. Visual comparison of these curves with data points indicate the deviance of observed experimental values from such distribution. Quantitative measures of such comparison are manifested in Table 2. The distribution of experimental results indicates the sensitivity of asphalt mixtures to these parameters which causes relatively large deviations from the normalized average curve. A comparison between average and deviation values at different times indicates that deviations tend to increase over time but appear to be approaching a limiting value of nearly 37% (Table 2).

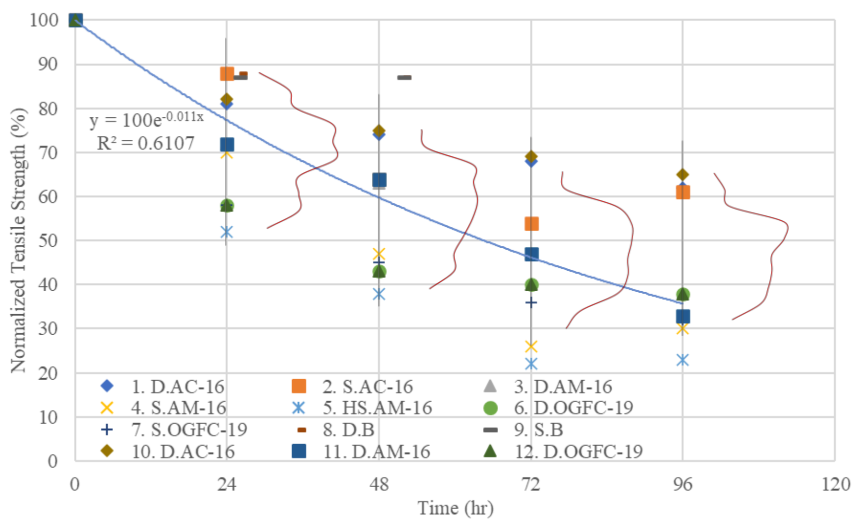

Figure 1. Observed trends of tensile strength reduction due to freeze-and-thaw cycles.

Table 2. Statistical measures of the tensile strength

Normalized Tensile Strength (%)	24-hr	48-hr	72-hr	96-hr
Mean	69.1	56.60	44.9	41.5
Standard deviation	12.22	13.84	15.69	15.23
Coefficient of Variation (%)	17.68	24.45	34.94	36.70

Figure 2 exhibits statistical limits for selected data in table 1. Almost add data points are within average plus/minus two standard deviations, which is nearly 95% probability. The HS.AM-16 specimen, a semi-open-graded asphalt mixture with about 12% air voids subject to 6% salt always under-perform with tensile strength below average minus one standard deviation, that is 84% probability line. Specimens subjected to distilled water typically perform better than average, except for D.OGFC-19, An open-graded friction courses with 18% air voids. This indicates the adverse impact of air voids on the strength of asphalt mixtures. Similarly, the S.AC-16, a dense-graded asphalt mixture with 6% air voids and 16 mm nominal maximum aggregate sizes performed better than average, even in presence of 3% salt. Statistical measures of data in figure 2 indicate that achieving the upper 16th percentile of performance is possible with the application of dense-graded asphalt mixtures only. These mixtures will experience less than 40% reduction in tensile strength.

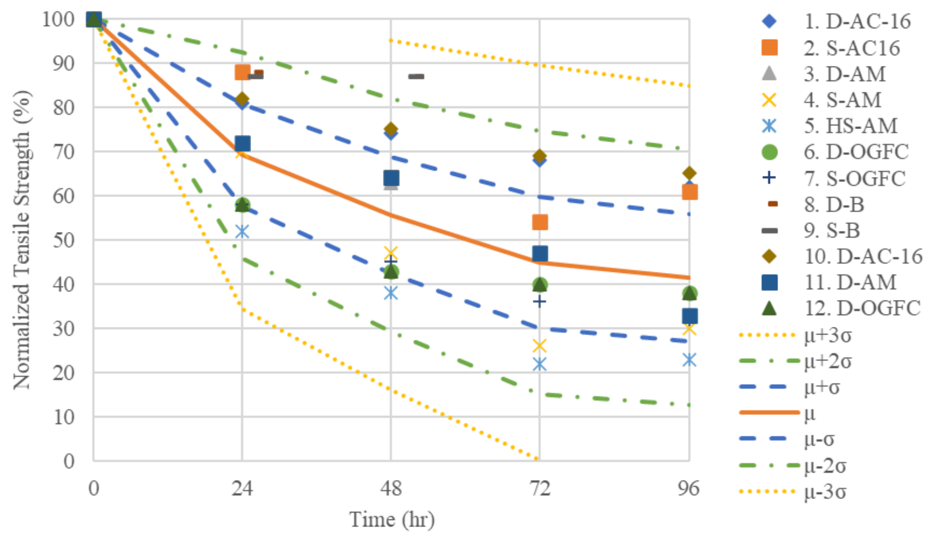

Figure 2. Statistical measures of normalized tensile strength values over time.

Table 3. Statistical measures of the weight loss

Normalized weight loss (%)	0-hr	24-hr	48-hr	72-hr	96-hr
Mean	-0.204	-0.322	-0.444	0.627	4.600
Standard deviation	0.316	0.291	0.556	1.874	4.942
Coefficient of Variation (%)	136	141	176	360	166

Weight Loss. Figure 3 shows the trends of weight loss over time for selected specimens as referenced in Table 1. Table 3 provides statistical measures for weight loss data. The red curves in Figure 3 represent the normal distribution diagram in each period of freeze-thaw. Similar to the previous case for tensile strength in Figure 1, visual comparison of these curves with data points indicate the deviance of observed experimental values from such distribution with quantitative measures of such comparison manifested in Table 3. These values are normalized to the mean value at time 0-hr, and hence statistical measures at initiation time represent a distribution of results for individual specimens, marked as a, b, and c in Figure 3. Mean values at 0, 24, and 48 hours indicate that most specimens had slight weight gain in the early stages due to the availability of air voids to absorb water, that is gaining weight without a change in the volume. After this steady phase, the weight loss begins. The long-term performance of mixtures is aligned with observed trends for the reduction of tensile strength values, as mixtures with high air void, contents exhibit higher weight loss. However, the skewness of distribution at 96-hr for high weight losses is substantially higher than those observed for low tensile strength values. Figure 4 shows that these results are out of mean plus/minus three standard deviation boundaries, with less than 2.5% probability.