Improving Specifications to Resist Frost Damage in Modern Concrete Mixtures

Pool Fund Study TPF-5-297

Led by Oklahoma DOT

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October, 2025

Acknowledgements

A big thanks goes out to Ron Curb, Gary Hook, Matt Romero, and Kenny Seward of the Oklahoma DOT for their valuable insights and help in leading this project and for hosting this pooled fund study. We also appreciate the support from the following DOTs. This project would not have been possible and could not have been completed without your assistance:

Colorado DOT, Pennsylvania DOT, Illinois DOT, Iowa DOT, Kansas DOT, Michigan DOT, Minnesota DOT, Nebraska Department of Roads, New York DOT, Wisconsin DOT, North Dakota DOT, Idaho DOT

We should also mention Mike Praul, Bob Conway, Jagan Guidimettla, Jim Grove, and Nicoli Morari of FHWA. This group provided tremendous feedback on the work.

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Introduction

Concrete is widely known as the building material of choice when a long-lasting structure is desired. However, concrete can be damaged when it is 1) wet and 2) exposed to freezing temperatures [1, 2]. The damage that occurs due to freezing and thawing can lead to premature deterioration, costly repairs, and the need to replace concrete infrastructure components well before they reach the end of their expected lifetimes. The most widely adopted approach to producing concrete with frost durability is to add an air-entraining admixture (AEA) while the concrete is being mixed.

Phase I of this project focused on establishing methods to measure the quality of the air void system or the air void distribution in fresh concrete, resistance of concrete to calcium oxychloride formation (CaOXY), and the impacts of pumping on the air void system in concrete. This work was valuable as it has led to many state DOTs to change their specifications to help them obtain improved air void systems.

Phase II attempts to have the same level of impact. The work focuses on the following subjects: i) recommendations to suppress CaOXY and validation that these work, ii) predicting the amount of freeze thaw damage based on local weather, and iii) investigating the impacts of concrete temperature on the return of air voids in pumped concrete. The work on CaOXY provides a blueprint on how to stop CaOXY by using a combination of air volume and supplementary cementitious content replacement. The work on the impacts of local weather provides important insights on ways to compare freeze thaw exposure in different locations and also how to use that information to design a concrete mixture. The final section on pumping shows that the air lost during pumping will return regardless of the temperature of the concrete.

1.1 Organization of this Document

This was a collaborative research project between research teams led by Dr. Tyler Ley at Oklahoma State University and Dr. Jason Weiss at Oregon State University. Each chapter in this document is a summary providing the key conclusions and most important data from the work. An appendix has been included for many of the chapters that provides more content. In most cases, each appendix is a peer reviewed journal paper that provides details about the methods and materials used, as well as a much more in depth discussion of the results and the data. This means that if there is a detail that a reader wants to know more about then they are encouraged to look at the corresponding appendix. The document was organized in this way so that a reader could quickly learn the key findings while also having access to all of the necessary details of interest.

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The Influence of Air Voids and Fluid Absorption on Salt-Induced Calcium Oxychloride Damage

1. Introduction

Premature deterioration in some portland cement concrete pavements is linked to deicing chemicals, particularly calcium and magnesium chloride. It has been shown in the field that these salts often accumulate in pavement joints that do not drain [1-4]. While low salt concentrations can increase the potential for freezing and thawing damage, higher concentrations can lead to the formation of solid phases like Friedel's salt (FS), Kuzel's salt, and calcium oxychloride (CaOXY).

CaOXY forms in a chemical reaction where calcium hydroxide ($Ca(OH)_2$) in the concrete reacts with a salt solution such as calcium chloride ($CaCl_2$+H_2O). The form of CaOXY most widely cited as responsible for concrete deterioration is CaOXY, $3Ca(OH)_2 \cdot CaCl_2 \cdot 12H_2O$ [2,3]. This reaction is reversible and depends on the chloride concentration and the temperature of the concrete. A phase diagram of the reaction is shown in Figure 1. When the temperature falls below the liquidus line, solid CaOXY forms; when it rises above this line, the solid reverts to a fluid. For instance, a 10% CaCl2 concentration can cause solid CaOXY to form at approximately room temperature [2].

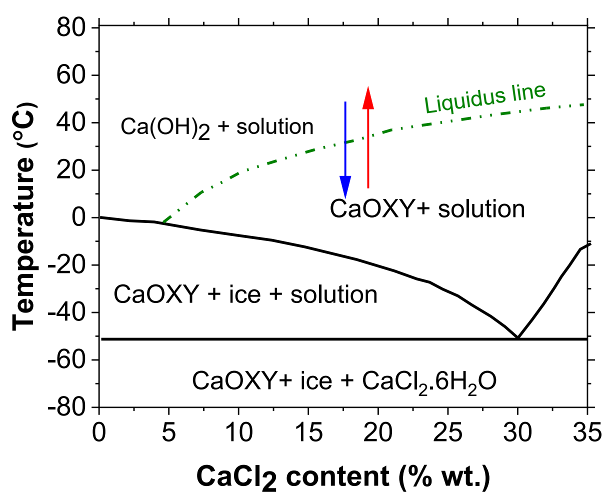


Figure 1. Phase diagram of $Ca(OH)_2$-$CaCl_2$-H_2O with Temperature and CaCl2 content [51]

The formation of CaOXY is particularly problematic because its volume is about 300% larger than the $Ca(OH)_2$ from which it forms [2,3]. This expansion can create pressure that exceeds the tensile strength of the paste, leading to damage. Previous studies have shown that damage development is more likely to occur upon heating than cooling [3]. It has also been suggested that damage increases in samples immersed in salt solution compared to those not in solution, suggesting that fluid absorption plays a crucial role [1,3].

To mitigate this damage, various methods have been suggested, including:

- Using supplementary cementitious materials (SCMs) to reduce $Ca(OH)_2$ content.
- Entraining air in the concrete to reduce the pressures during expansion.
- Applying topical treatments to act as a barrier between the concrete and deicing salts.
- Carbonating the concrete to reduce $Ca(OH)_2$ and form a protective barrier.
- Reducing the paste content to decrease the amount of $Ca(OH)_2$ available for reaction.

Current specifications, such as AASHTO R101, limit the amount of CaOXY to 15g/100g of paste based on previous observations. Unfortunately, these limits don't account for other factors like the paste volume or air content. This work provides more insight into these parameters to improve specifications [5].

2. Experimental Approach

The study prepared 12 different concrete mixtures with varying air volume and $Ca(OH)_2$ contents. The $Ca(OH)_2$ content was controlled by replacing 0% to 40% of the cement with Class C fly ash (FA) by mass. For each replacement level, a low (≈2%) and high (≈5%) air volume was targeted. The water-to-cementitious material ratio was kept constant at 0.45 for all mixtures. The mortar was sieved from the concrete by using a #4 sieve. The mortar was added to cylinders and these cylinders were cured for 91 days in a sealed condition at 23^{o}C.

After curing, the samples were subjected to a salt damage testing procedure involving storing samples in a 20% $CaCl_2$ solution and exposing the samples to 15 temperature cycles from 50^{o}C to 5^{o}C. This temperature range was chosen to ensure that the concrete was not frozen to ensure that any damage was from CaOXY formation and not ice. According to the phase diagram for the $Ca(OH)_2$–$CaCl_2$–H_2O system, solid CaOXY forms in the pores at 5^{o}C and becomes a liquid at 50^{o}C.

The experiments used three conditions:

1. **Condition #1 - In salt solution:** Samples were immersed in a 20% $CaCl_2$ solution during temperature cycling to study the impact of fluid absorption.

2. **Condition #2 - Sealed:** Samples were wrapped in aluminum tape to prevent fluid from entering and to limit evaporation.

3. **Condition #3 - In lime solution:** Control samples were immersed in a lime-water solution with no salt.

The researchers measured the mass change and the residual strain at the end of each temperature cycle. The residual strain is the overall expansion of the sample and as an indicator of damage within the sample.

3. **Key Findings**

3.1 Role of Fluid Absorption

The results showed that samples exposed to the salt solution during temperature cycling experienced a greater increase in the residual strain than samples that were sealed or exposed to lime solution. This indicates that fluid absorption is a critical factor for CaOXY development. These results are shown in Figure 2.

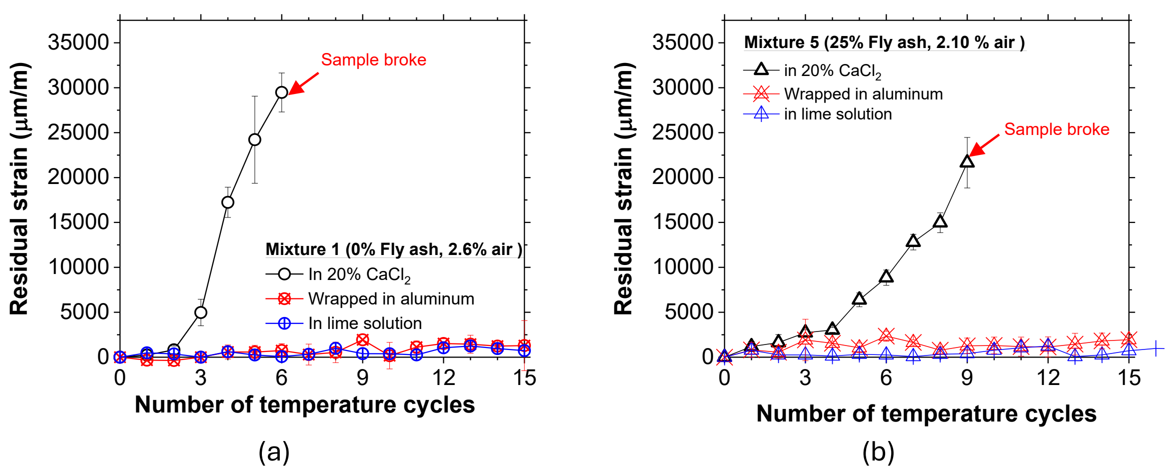


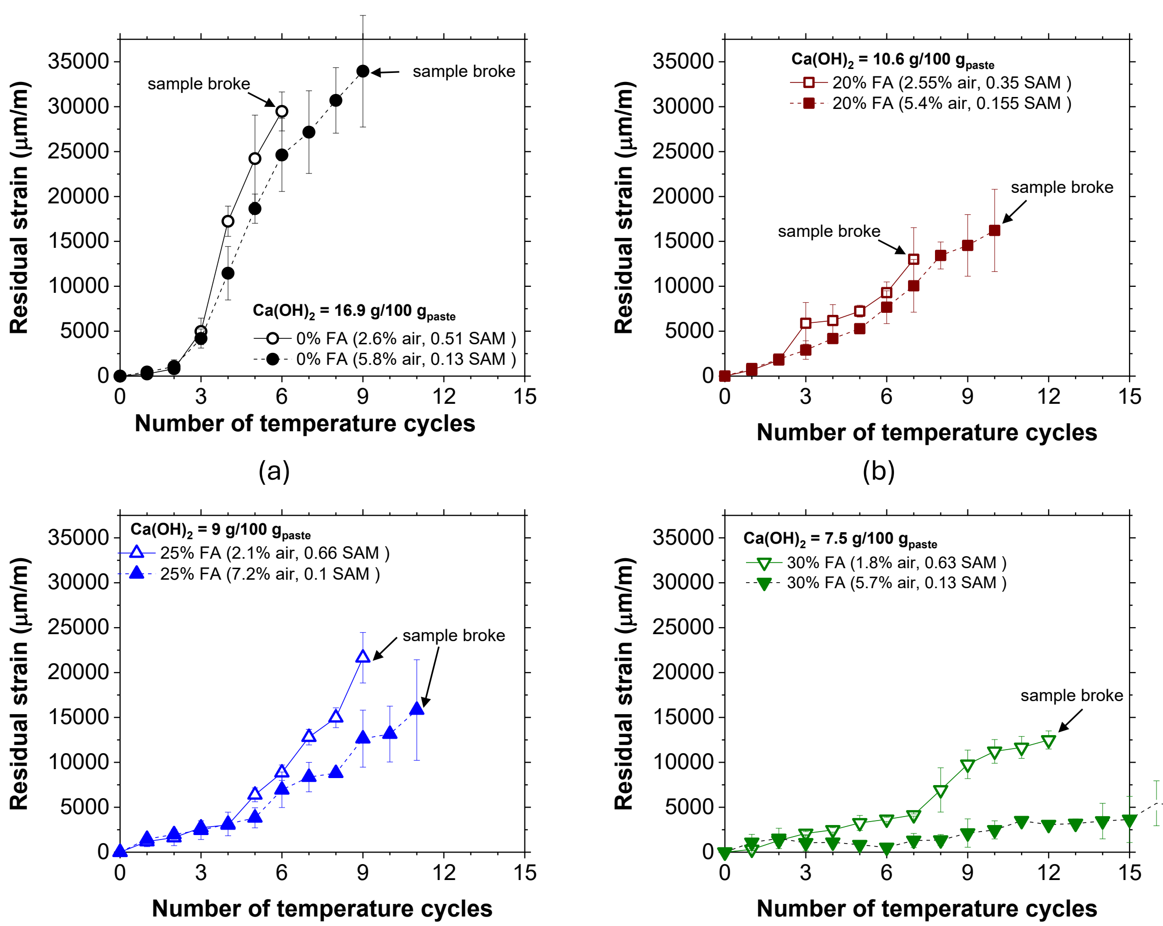
Figure 2. Residual strain with respect to the number of cycles for the three different conditions tested in this study (a) in 0% fly ash (high $Ca(OH)_2$ content), (b) in 25% fly ash (lower $Ca(OH)_2$ content)

The samples in the salt solution gained mass before visible damage occurred, while the sealed samples showed a slight mass loss due to evaporation. This suggests that the CaOXY at lower temperatures shrinks. This shrinkage will create a suction that pulls fluid from the surrounding solution into the pores. As the temperature increases and the solid CaOXY turns into a liquid, the liquid causes large pressures that can damage the concrete if there is no empty space to accommodate it.

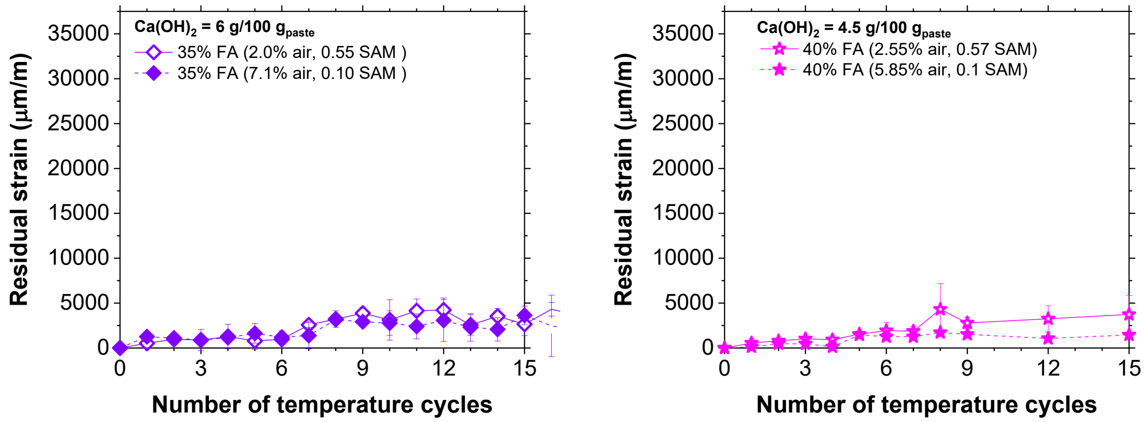
3.2 Influence of Air Content and Fly Ash

The study also examined the impact of air volume on the damage. The air voids seem to provide "space" for the volume changes that CaOXY has. The testing results are shown in Figure 3. The results showed that:

- In mixtures with high $Ca(OH)_2$ content (0-20% fly ash replacement), the air volume did not significantly influence the damage. The amount of CaOXY formed was so large that the available void space was insufficient to prevent expansion and damage.
- In mixtures with low $Ca(OH)_2$ content (35-40% fly ash replacement), damage was negligible regardless of air void content. This is because the high fly ash content reduced the available $Ca(OH)_2$, thus limiting CaOXY formation and expansion.
- In mixtures with moderate $Ca(OH)_2$ content (25-30% fly ash replacement), the air void content was a significant factor. Samples with a higher air volumes showed improved resistance to salt damage compared to those with lower air volumes.



(c) (d)



(e) (f)

Figure 3. Residual strain with respect to the number of temperature cycle for mortar samples with 2 different air void content (a) Mixture 1 and 2, (b) Mixture 3 and 4, (c) Mixture 5 and 6, (d) Mixture 7 and 8, (e) Mixture 9 and 10, (f) Mixture 11 and 12.

This led to a reevaluation of the AASHTO R101 limit for CaOXY content. For the low-air-content samples, the limit of 15g of CaOXY/100g of paste was a good indicator for damage. However, for samples with approximately 5% air content, the threshold for damage was about 8g CaOXY/100g paste of $Ca(OH)_2$. This suggests that the threshold for CaOXY induced damage is not a fixed number but depends on the air void volume.

Numerical modeling was done to extend these findings to a wider range of paste contents and air volumes. The modeling found that the number of temperature cycles to fill voids increased with both the fly ash content (or lower $Ca(OH)_2$) and the air-to-paste content ratio. This reinforces the idea that concrete with high increased air volume and low paste volume will be more resistant to CaOXY salt damage.

4. Conclusion

This study provides a more comprehensive explanation of CaOXY-induced damage in concrete by incorporating fluid absorption, paste volume, and air content as key parameters. The findings demonstrate that:

- The when salt solution surrounds the sample that the pumping effect caused by the CaOXY phase changes is an important mechanism for concrete damage.
- The air volume of a concrete mixture is crucial in mitigating salt damage, particularly in mixtures with a fly ash replacement between 25% to 30%. The air voids seem to provide space to accommodate the volume changes caused by CaOXY formation and dissolution.

- The current AASHTO R101 limit for CaOXY, while a good starting point, may be conservative for mixtures with at least 5% air content, as these can tolerate a higher amount of CaOXY before damage occurs. This suggests that future specifications should consider a material's air content and paste volume in addition to its CaOXY content.

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Quantifying Calcium Oxychloride Formation Using Micro-Computed Tomography

1. Introduction

This work builds on the research in the previous chapter and provides direct observations of the damage mechanism of calcium oxychloride (CaOXY) damage in concrete. The research uses simple length measurement testing and X-ray micro-computed tomography (Micro-CT) to non-destructively observe the progressive damage in the samples as they expand and become damaged.

2. Key Findings

The research compares two mortars that were sieved from concrete. Both mixtures have similar air contents and one mixture uses 20% fly ash replacement and uses 40% fly ash replacement of the cement in the mixture. These different replacement levels of fly ash were chosen as the sample with 20% fly ash replacement should not be enough to suppress CaOXY and the 40% fly ash replacement is expected to stop the expansion. The expansion of these samples is shown in Figure 1. The key difference between the two mixtures is their calcium hydroxide ($Ca(OH)_2$) content; the 40% fly ash mix has significantly less $Ca(OH)_2$ due to the pozzolanic reaction of the fly ash.

The $Ca(OH)_2$ content in the 20% fly ash and 40% fly ash mixtures was determined to be equal to 10.6 $g/100g_{paste}$ and 4.5 $g/100g_{paste}$ respectively [1]. This decrease in $Ca(OH)_2$ content is caused by the pozzolanic reaction with fly ash that was added. The lower amount of $Ca(OH)_2$ will decrease the CaOXY content, which is expected to decrease the damage to the sample.

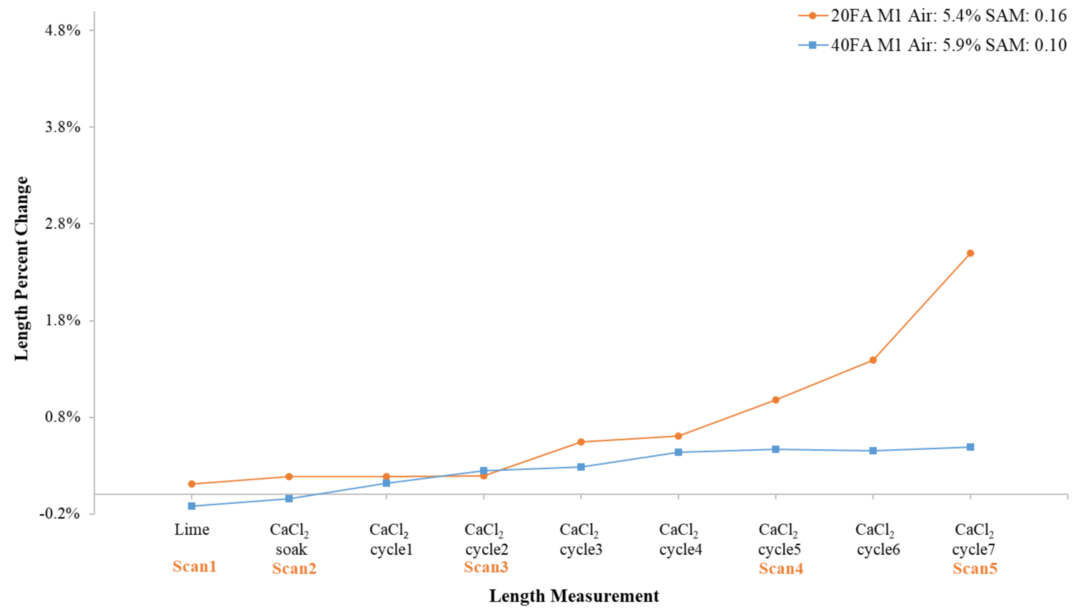

Figure 1. Length measurement versus percent change.

2.1 Damage Gradient

The study confirms that damage begins at the surface of the concrete and progresses inward. The sample with 20% fly ash showed a substantial increase in cracking near the surface (0-1.5 mm deep), while the cracking decreased with depth. This is a direct observation of the damage gradient. This is shown in Figure 2. The 40% fly ash sample did not show cracking.

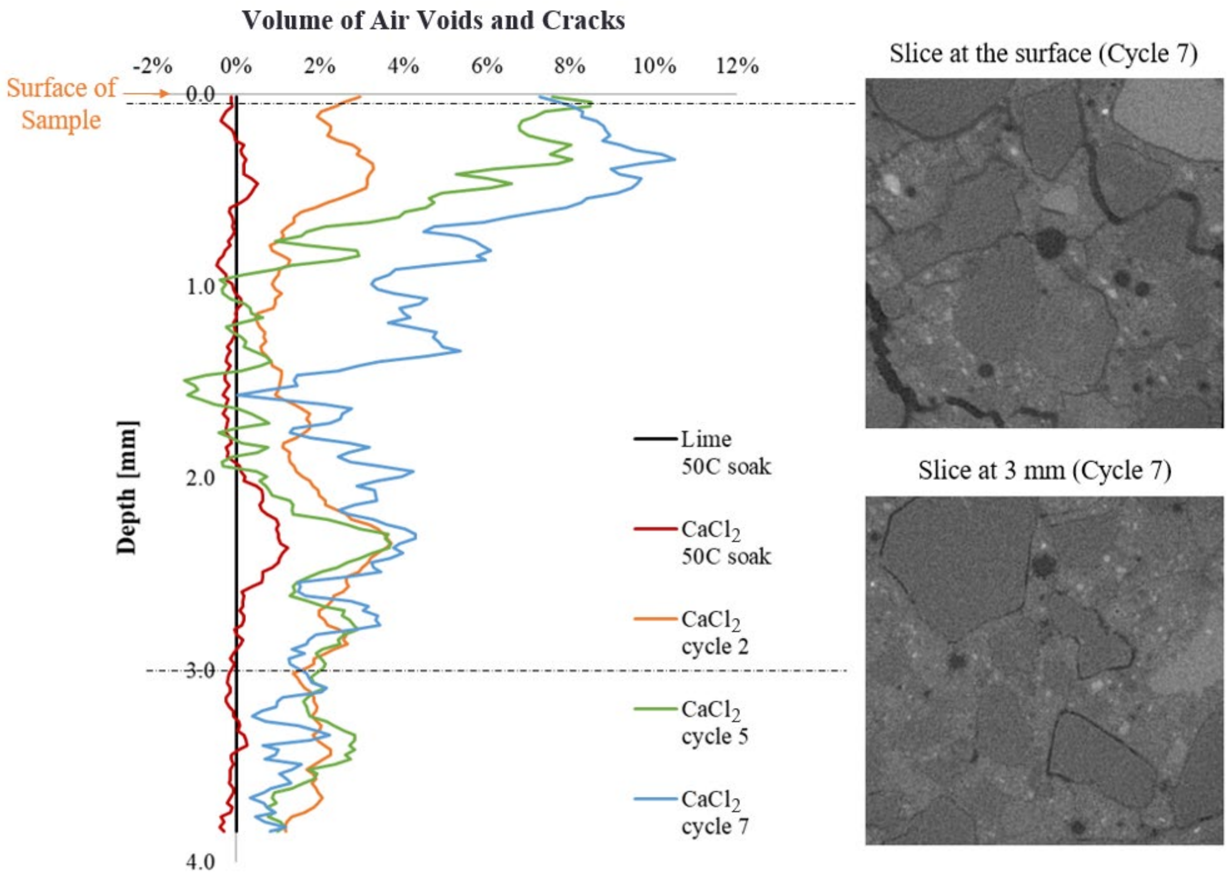

Figure 2. Change in the total volume of air over the depth of the 20 percent fly ash sample. Each image is 3 mm x 3 mm in size.

2.2 Location of Cracking

Cracks were primarily observed in the transition zone around the aggregates. This is likely because the transition zone is where higher concentrations of $Ca(OH)_2$ are found, making it a prime location for the formation of expansive CaOXY. An example of the change in cracking measured by micro-CT is shown in Figure 3.

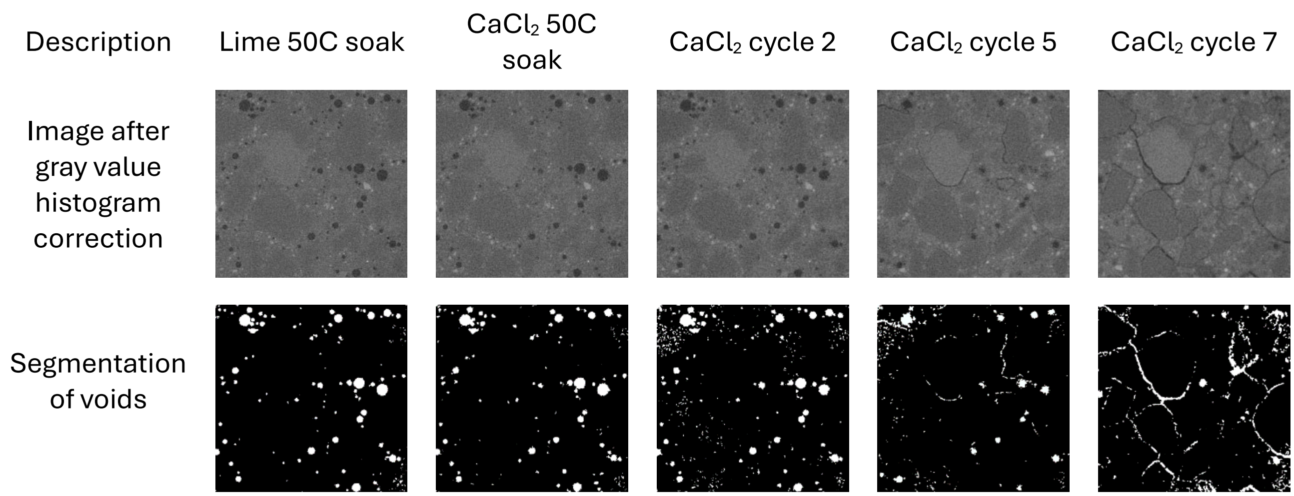

Figure 3. Images from the grayscale histogram correction process and segmentation of voids for the 20FA M1 sample. Each image is 3 mm x 3 mm in size.

2.3 Fly Ash as a Mitigating Factor

The most significant finding is the stark difference in performance between the two mixtures. The 20% fly ash sample experienced substantial damage, showing a steady increase in length and significant cracking. In contrast, the 40% fly ash sample exhibited minimal length change and no observable cracking. This confirms that using enough fly ash in the mixture will prevent CaOXY damage by reducing the available $Ca(OH)_2$ needed for the reaction.

2.4 Air Void Infilling

A critical aspect of the damage mechanism is the filling of air voids. The Micro-CT scans showed that in the 20% fly ash sample, the air voids filled a solid product. This infilling was progressive, with the voids losing up to 70% of their volume by the end of the test. A graph summarizing the performance is shown in Figure 4. This process reduces the concrete's ability to resist both CaOXY and freeze-thaw damage, explaining why this type of deterioration can be so severe in the field. The 40% fly ash sample showed almost no change in air void volume.

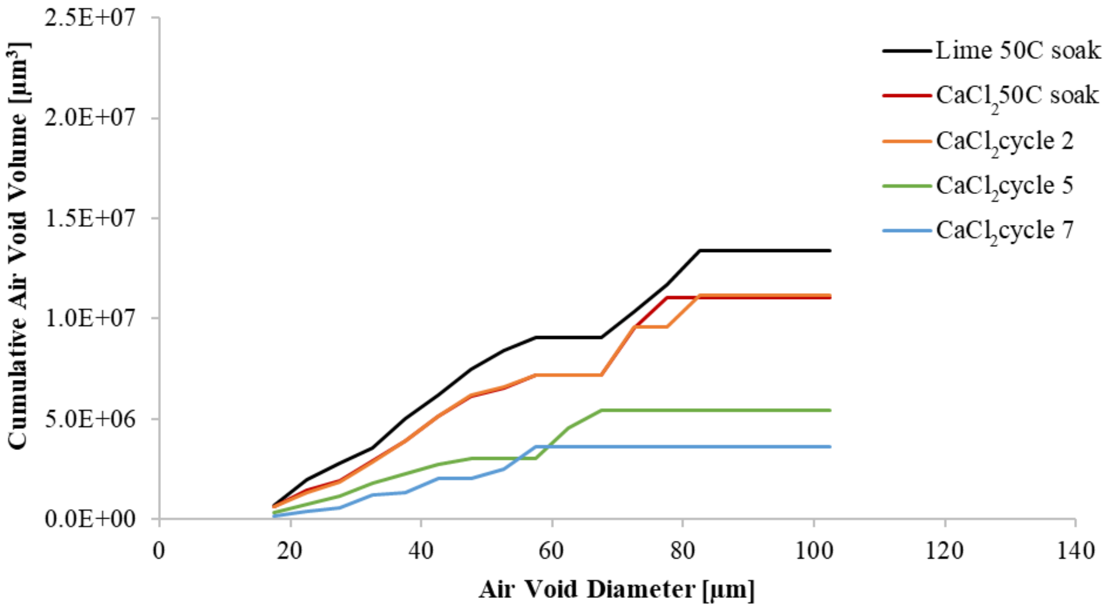

Figure 4. Cumulative air void volume for the 20% fly ash sample. The results reported do not include cracks.

2.5 Temperature Cycling

The damage can occur at moderate temperatures, not just below freezing. This is an important consideration because it means the deterioration can happen throughout the year whenever deicing salts are present.

3. Practical Significance

This study provides direct evidence that an increase in fly ash content can be highly effective in mitigating CaOXY damage. While air entrainment is crucial, this research suggests it only provides temporary protection if there is enough $Ca(OH)_2$ to facilitate the reaction. A combination of adequate air entrainment and a high level of fly ash replacement (around 30% or more as suggested by previous publications) appears to be a robust solution to prevent this form of concrete deterioration in areas exposed to deicing chemicals.

References

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Field-Based Measurement of Freeze–Thaw Damage in Cementitious Materials

1. Introduction

This work uses field instrumentation to directly measured the Degree of Saturation (DOS), freezing, and freeze thaw cycles where damage can occur. These are called damaging freeze thaw cycles in this work. These measurements were taken at 42 locations across 14 U.S. states. The core finding is that freeze-thaw damage is not caused by freezing temperatures alone but by the coincidence of freezing events with a high DOS, a factor that can vary significantly within the same region.

2. The Problem with Current Methods

Current standards like the LTPP Climate Region Classification categorize freeze-thaw risk based on broad climate data, such as precipitation and freezing index. This approach can be misleading because it overlooks site-specific conditions. For instance, a region may have a high freezing index (indicating many freezing days) but low moisture content, which would result in minimal or no damage to the concrete. Conversely, a region with fewer freezing days but consistently high moisture levels could be at a greater risk of damage.

3. The Study's Methodology

The researchers used a novel, field-based method. Mortar specimens were prepared and equipped with thermocouples and stainless steel rods at different depths to measure temperature and electrical resistivity. This instrumentation allowed for the real-time, in-situ calculation of the DOS, and the detection of freezing events. The specimens were intentionally designed to simulate poor drainage conditions to capture a worst-case scenario. The instrumentation is shown in Figures 1, 2, and 3.

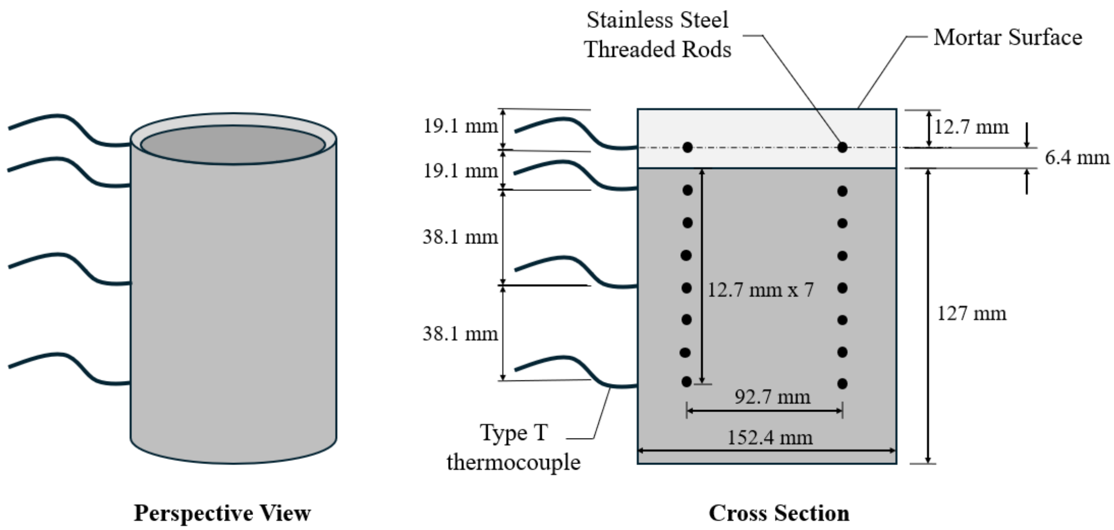

Figure 1: Instrumentation layout for the mortar samples used in the field (adapted from [29]).

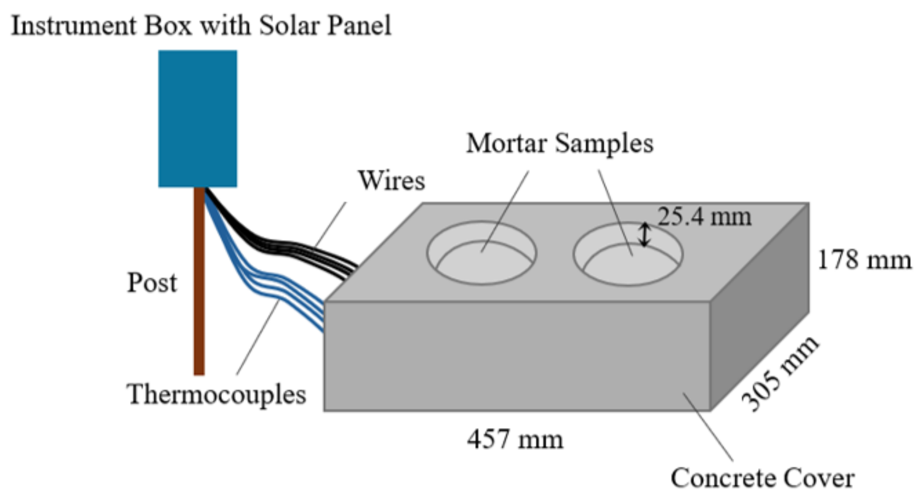

Figure 2: Schematic illustration of the experimental instrumentation setup used for the field samples. The concrete block and its connection to the instrument box are shown with a solar panel.

Figure 3: Installed mortar samples in the field, with the instrumentation box and solar panel set up for data collection**.**

The instruments were able to determine if a freezing event was "damaging" if it occurred when the DOS of the concrete was above a critical threshold of 80%. This threshold was chosen as a conservative lower limit where freeze-thaw damage is likely to occur [1-4]. The location of each of these instruments is shown in Figure 4. Figure 5 shows the total number of freeze thaw cycles and the total number of damaging freeze thaw cycles for the different instruments used.

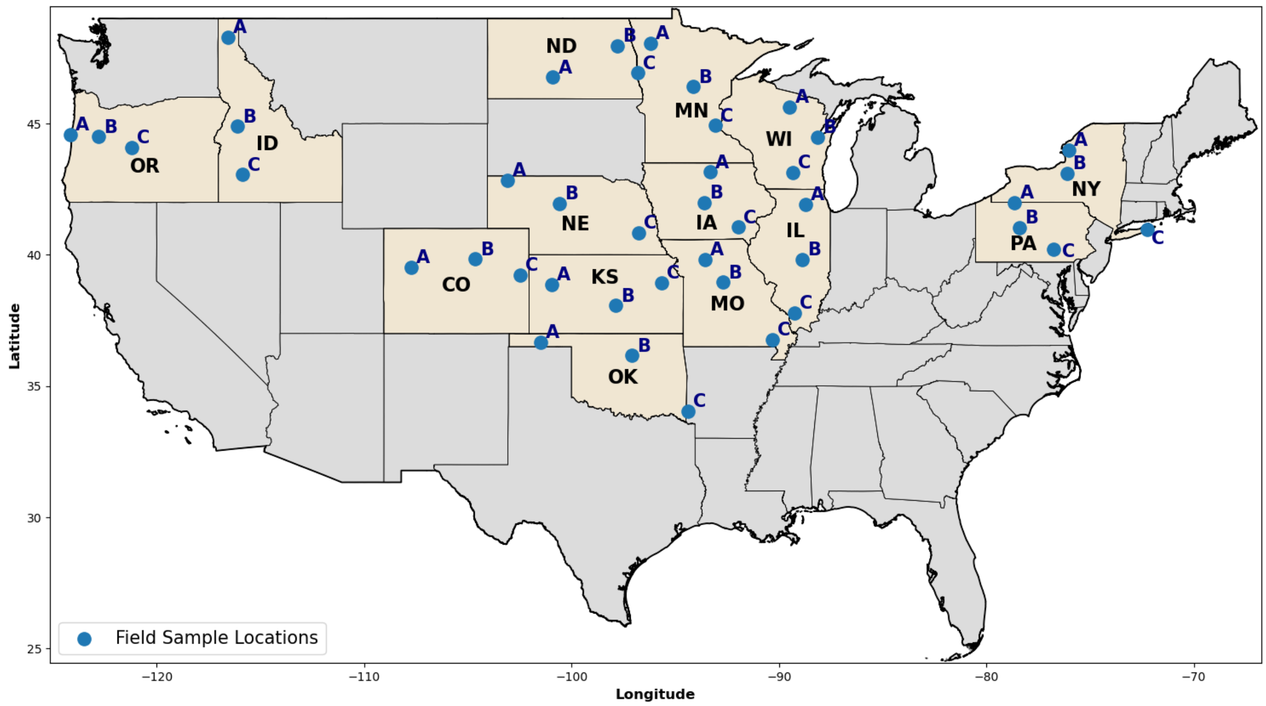

Figure 4: Field sample locations across 14 U.S. states, with sites labeled A–C within each state.

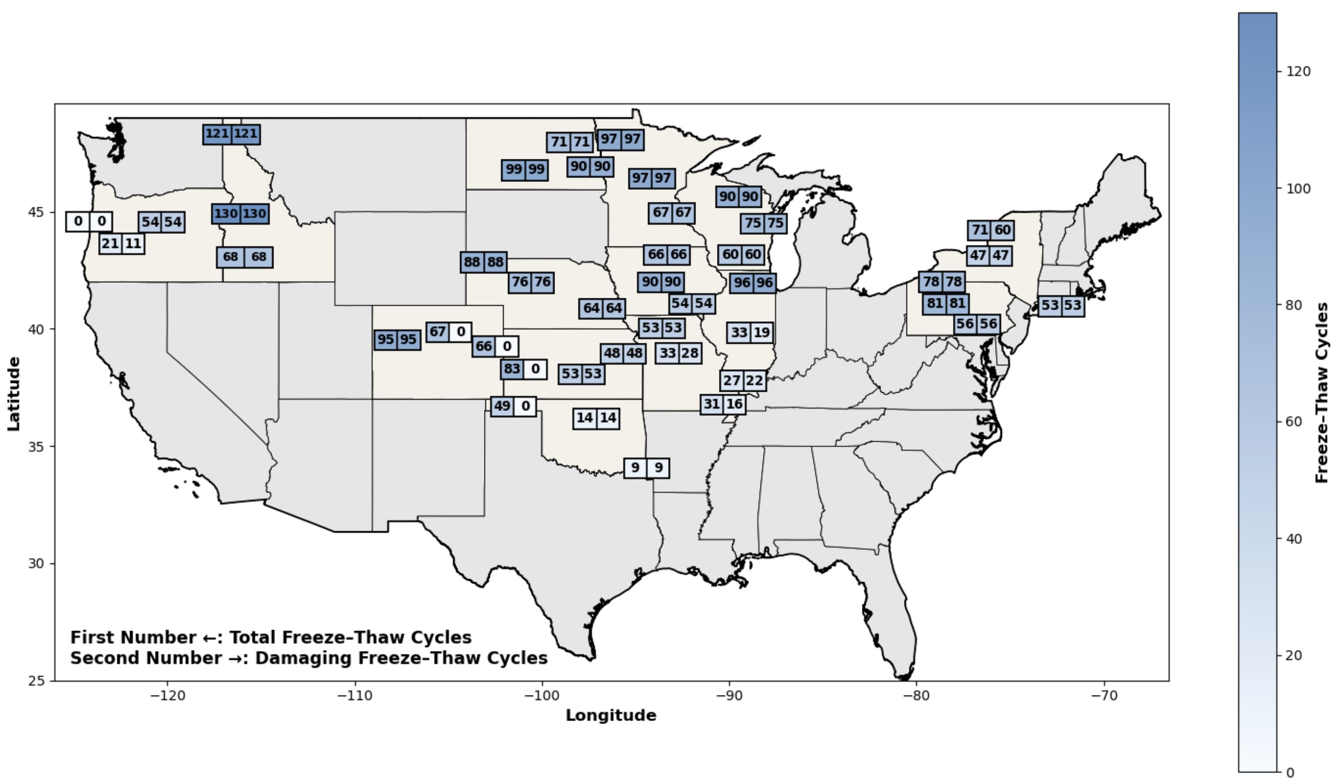

Figure 5: Total and damaging field-measured freeze–thaw cycles during winter 2020–2021.

4. Different Types of Exposure

The study identified four distinct freeze-thaw exposure scenarios, providing a more nuanced understanding of concrete performance in different environments:

1. **Wet + Freeze-Thaw:** In regions like Minnesota, North Dakota, and Wisconsin, the DOS consistently remained above the 80% threshold during the winter. As a result, nearly all freeze-thaw cycles were damaging. This confirms that in these climates, the risk from freeze thaw damage is high.
2. **Dry + Freeze-Thaw:** Locations in states such as eastern Colorado and western Oklahoma, and western Kansas experienced a high number of freeze-thaw cycles, but because the DOS remained below 80%, these cycles were damaging. This indicates that for certain areas that air entrained concrete may not be required unless the concrete will become saturated from some other event besides the weather.
3. **Wet + Low Freeze-Thaw:** Some locations, in western Oregon and central Oklahoma, had a DOS that could cause damage but the region experienced very few freezing events. While any freezing that did occur was damaging, the overall limited number of cycles meant the total damage was low.
4. **Variable Saturation + Freeze-Thaw:** At sites such as in Illinois and Missouri, the DOS fluctuated above and below the 80% threshold. This resulted in a mix of damaging and non-damaging cycles. This demonstrates the importance of considering moisture fluctuations for a location. The timing of a freezing event relative to a period of high saturation is important to determine damage.

These measurements are going to be an important part of predicting freeze thaw damage in concrete in the following sections. A map of these locations is shown in Figure 6.

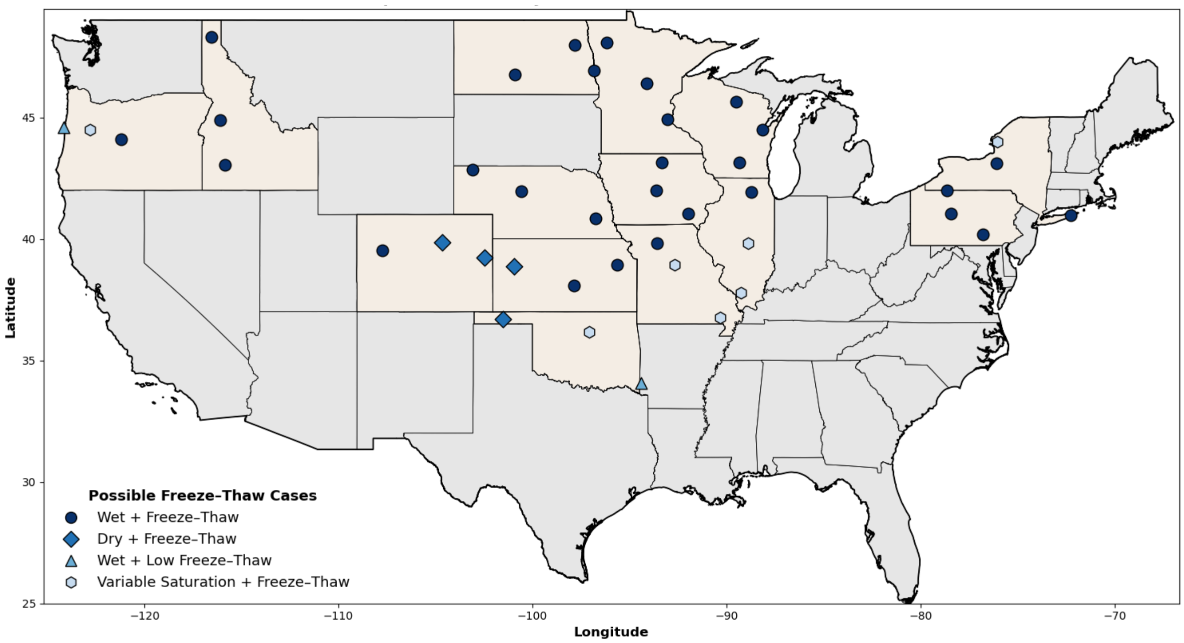

Figure 6: Geographic distribution of freeze-thaw cases assigned to each field location.

5. Conclusion

This research provides a field-validated framework for assessing freeze-thaw risk that goes beyond traditional, broad climate classifications. The findings suggest that:

- Site-specific measurements are important to accurately assessing freeze-thaw damage risk.
- The required air content and durability design for concrete can vary significantly within a single state or region, depending on the local moisture and temperature conditions.
- The concept of a "damaging" freeze-thaw cycle must includes both a freezing temperature and a high moisture content, as freezing alone does not cause deterioration if the concrete is dry.
- This data lays the groundwork for developing a measurement-based mapping system to better inform concrete durability design and avoid both under-design and overly conservative, costly solutions.

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Predicting Concrete Freeze–Thaw Damage with Weather Data Based Machine Learning

This work presents a field-validated machine learning model that uses readily available local weather data to accurately predict the Degree of Saturation (DOS) and the number of damaging freeze-thaw (FT) cycles in concrete. This framework offers a data-driven tool to replace generalized, prescriptive durability standards, providing engineers with a method to tailor concrete mixtures to the actual, site-specific freeze-thaw risk.

The model achieved an average DOS prediction accuracy of 89% and predicted damaging FT cycles within 15% of the measured value with a 95% confidence interval. This demonstrates the robustness of the model across various climates and years.

1.1 Current Specifications

Current concrete durability specifications (like ACI 318 and ACI 201.2R) require engineers to select exposure classes based on engineering judgement. This forces engineers to make decisions regarding local weather, the saturation level of the concrete, and the frequency of damaging cycles that are not intuitive. This model addresses this gap by directly linking six key weather parameters to the DOS of the concrete and uses air temperature to determine the number of damaging FT cycles.

1.2 Linking Weather to Concrete DOS

The research utilized a comprehensive field dataset collected over four years from 42 locations across 14 U.S. states. The model then classifies the DOS of the concrete based on the environmental inputs.

- **Critical Thresholds:** The model classifies the average monthly DOS into three practical categories reflecting risk:
    - < 80% - Minimal risk.
    - 80% to 90% - Moderate risk (requires a designed air void system).
    - > 90% - High risk (requires a highly effective air void system).
- **Weather Parameters:** Six environmental variables that influence the DOS of the concrete were used. These include: Air Temperature, Total Precipitation, Relative Humidity, Solar Radiation GHI, Wind Speed, and Air Pressure. These parameters were chosen based on the literature to determine the soil moisture content.
- **Regional Adaptability:** To account for significant climatic variation, the sites were grouped into four distinct regions: Northwest, South, North, and Northeast. This

approach confirmed that weather feature thresholds vary significantly by region. **Genetic Algorithms (GA) Optimization:** Conventional machine learning models performed poorly (< 56% accurate) due to the complex, non-linear relationships between the six weather inputs and the highly variable DOS. A Genetic Algorithm was used, which optimized region-specific weather thresholds to accurately classify the DOS into the correct risk category. This method achieved an average DOS prediction accuracy of 89% with one season of training and three years of validation.

2. Determining Damaging Freeze-Thaw Cycles

For this work, a freeze-thaw cycle is considered damaging if it occurs when the DOS is 80% or higher.

- **Air Temperature as a Proxy:** Statistical analysis showed a very strong linear correlation ($r > 0.93$) and no significant difference between the measured air temperature and the concrete temperature at 51 mm below the surface. This allows the model to use readily available air temperature data as a reliable proxy for concrete temperature, making the model scalable without needing embedded sensors.

- **Simplified Freezing Temperatures:** The temperature at which water freezes in concrete is dependent on DOS (higher DOS = warmer freezing temperature). To simplify prediction, a single optimal freezing temperature was assigned to each predicted DOS category based on extensive testing:

  DOS < 80%: -4.0 °C

  DOS 80% to 90%: -3.5 °C

  DOS >90%: -1.5 °C

By combining the predicted DOS category (and its associated freezing temperature) with local air temperature records, the model can predict the total and damaging FT cycles that occur within 15% of the measured value with a 95% confidence interval. An overview of the results for the different regions is shown in Table 1. The percent difference between the measured values is compared to the predicted value.

Table 1

Regional and Overall Percent Differences Between Predicted and Measured Total and Damaging Freeze–Thaw Cycles Across 42 Locations Over Three Years

Region	Winter Season		September 2021 – April 2022		September 2022 – April 2023		September 2023 – April 2024	
	State	Location	FT Cycles % Difference*		FT Cycles % Difference*		FT Cycles % Difference*	
			Total	Damaging	Total	Damaging	Total	Damaging
North	North Dakota	Bismarck Site	0	-2	0	0	NA	NA
		Grand Forks Site	0	-8	0	0	NA	NA
		Fargo Site	0	-11	0	0	NA	NA
	Minnesota	Baxter	0	-5	0	0	-4	-4
		Maplewood	6	11	0	0	2	2
		Thief River Falls	3	-4	0	5	-4	-2
	Wisconsin	Green Bay	-4	-1	-8	8	NA	NA
		Madison	-8	-10	-4	-4	0	0
		Rhinelander	-5	1	0	2	NA	NA
	Iowa	Ames	-3	1	-2	-3	NA	NA
		Fairfield	-8	-8	-7	-7	0	0
		Mason City	8	-3	-4	-4	0	0
	Nebraska	Lincoln	-7	-7	0	0	14	8
		Thedford	2	-6	0	-8	3	3
		Chadron	-5	4	0	0	1	10
	Illinois	Dixon (Northern)	-4	-1	-2	10	NA	NA
	Missouri	Northwest District	-5	-5	0	0	-3	-3
	Average (%)		-2	-3	-2	0	1	1
	Standard Deviation		5	6	3	5	5	5
South	Colorado	Denver	0	0	1	0	-1	0
		Seibert	-4	0	-4	0	0	0
		Glenwood	-1	4	-5	0	-1	-1
	Kansas	Oakley	-1	0	0	0	1	0
		Hutchinson	2	-12	0	-8	4	-9
		Topeka	-10	-10	-15	-7	-4	-4
	Oklahoma	Cooper Lab	0	0	0	9	6	-11
		McCurtain County	0	0	0	-9	8	-11
		Texas County	0	0	0	0	0	0
	Illinois	Spring Field (Central)	-5	-10	-12	-10	12	12
		Carbondale (Southern)	0	-11	0	-12	13	12
	Missouri	Central Laboratory	0	-12	0	-12	6	-14
		Southeast District	-3	-13	0	13	0	0
	Average (%)		-2	-5	-3	-3	3	-3
	Standard Deviation		3	6	5	8	5	7
Northwest	Oregon	Bend	-10	-12	0	-4	NA	NA
		Hinsdale Wave Research Lab	-8	0	-9	-12	NA	NA
		Newport	0	0	0	0	0	0
	Idaho	Coeur d Alene US-95	5	-5	0	2	-1	14
		Mt Home I-84	-12	-12	0	-15	-7	-12
		Paddy Flat SH-55	9	2	0	7	-5	-5
	Average (%)		-3	-4	-2	-4	-3	-1
	Standard Deviation		9	6	4	8	3	11
Northeast	Pennsylvania	Clearfield	-5	10	0	0	-3	-3
		Cyclone	-8	10	0	0	-6	-6
		Harrisburg	-8	-8	0	-2	7	7
	New York	Watertown	0	-6	4	-11	3	3
		Clifton Park	-8	4	-10	-13	4	4
		Hauppauge	0	11	0	0	10	10
	Average (%)		-5	4	-1	-4	3	3
	Standard Deviation		4	9	5	6	6	6
Average Difference Across All Regions & Years (%)			Total FT Cycles		-1	Damaging FT Cycles		-2
Standard Deviation Across All Regions & Years (%)					5			7
Maximum (% Difference)					14			14
Minimum (% Difference)					-15			-15

*Percent Error (%) = $\frac{Measured\ FT\ Cycles - Predicted\ FT\ Cycles}{Measured\ FT\ Cycles}\ x\ 100$

3. Practical Significance

This work delivers a scalable and reliable tool for assessing freeze-thaw risk that is superior to current prescriptive methods. This can allow the following benefits:

1. Engineers can use the model to input project location and expected local weather conditions to obtain a precise number of damaging freeze thaw cycles and the DOS. This enables a tailored concrete design for the exposure level rather than adopting a one-size-fits-all approach.

2. The framework can be extended into user-friendly freeze-thaw risk maps or web tools. These tools could provide transportation agencies with forecasts of potential freeze-thaw damage based on historical or simulated future climate data, supporting data-informed decision-making for asset management, construction planning, and infrastructure maintenance. This will be discussed in the next chapter.

Creating Maps of Freeze–Thaw Exposure for Concrete

1. Introduction

The field measurements and machine learning are combined to create freeze thaw risk maps for concrete based on a data-driven approach. This moves beyond generalized climate zones toward a performance-based assessment that quantifies damaging freeze-thaw cycles. The developed tool is helpful to ensure the long-term durability of concrete infrastructure.

2. Methodology

The maps in this study used data from 24 years of weather data (September to April, 2000–2024) from 574 weather stations across 14 U.S. states. The individual predictions from the 574 stations were transformed into a continuous maps using Inverse Distance Weighting (IDW) interpolation, followed by median and Gaussian smoothing to ensure visual clarity and reduce local noise.

The locations of the weather stations are shown in Figure 1. Predictions are made in the same regions where the field data was measured. This means that there are regions where a prediction is not made but this is because there is no field data to validate these predictions. Extending these predictions to other locations is an area of future work.

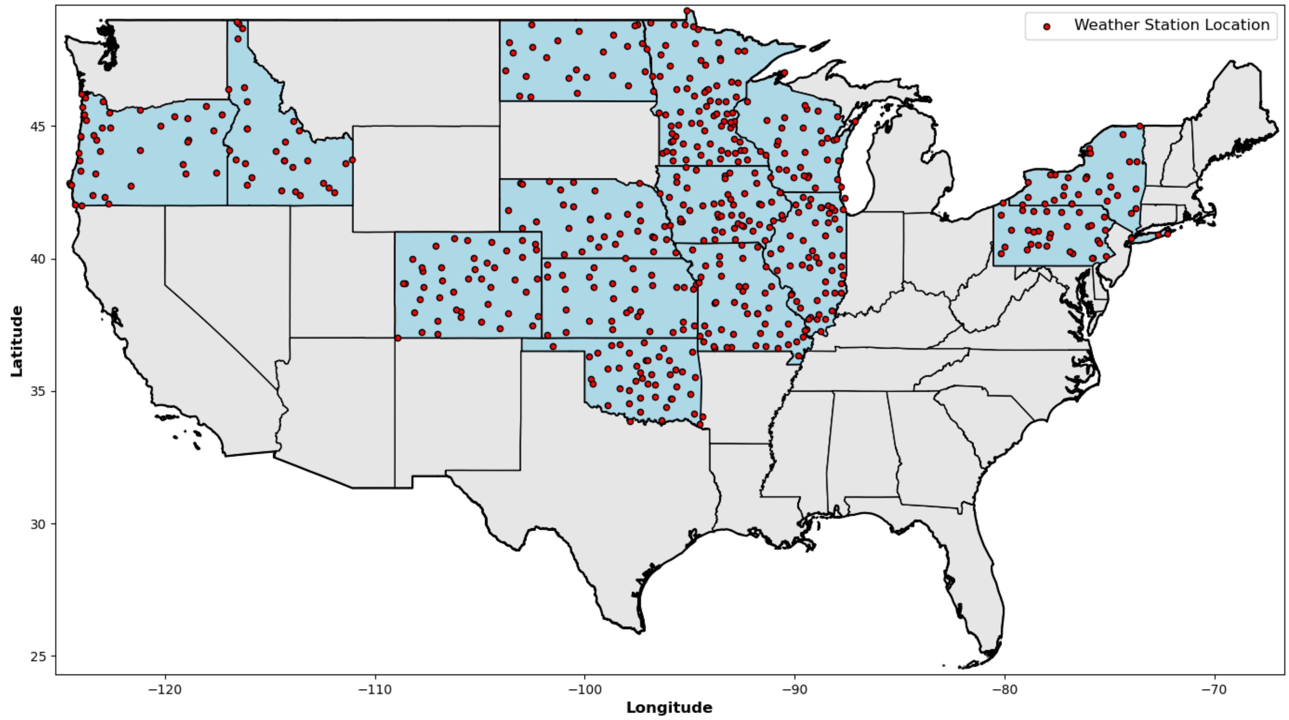
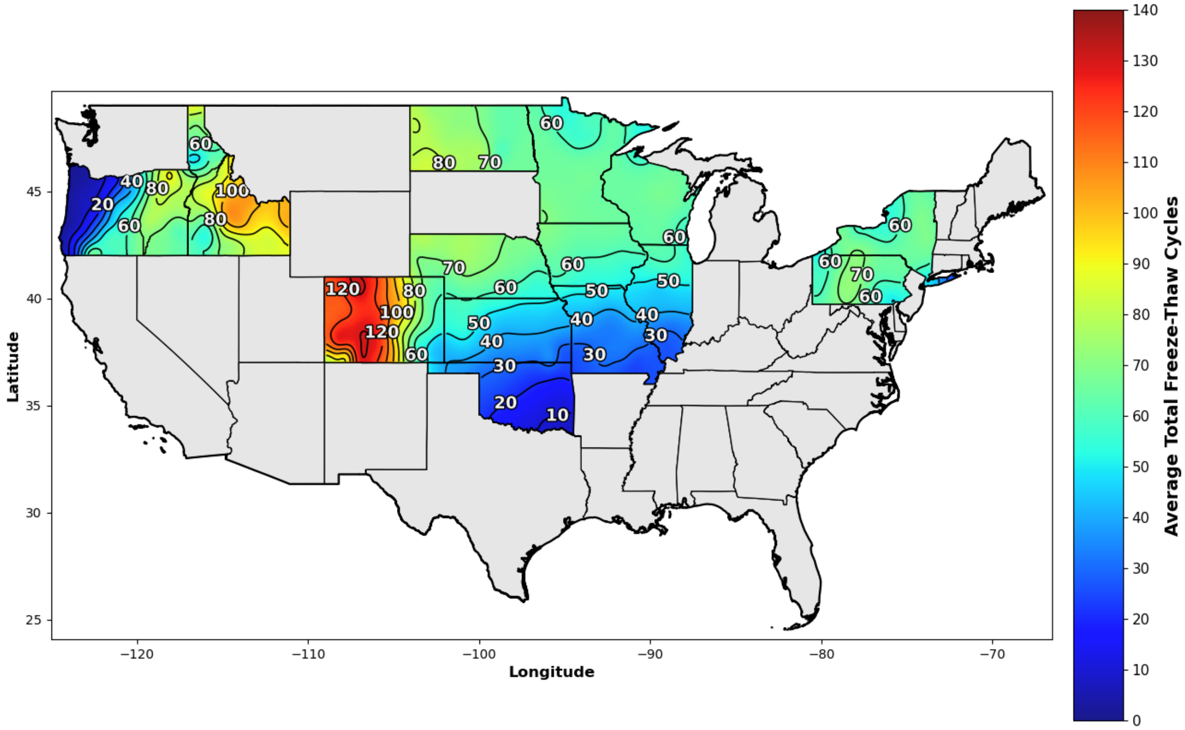


Figure 1: Locations of weather stations used for predicting freeze-thaw cycles in the states analyzed.

3. Results

Figure 2 shows the number of predicted damaging freeze thaw cycles for the regions investigated. The data is shown as a contour map. The reader should remember that a damaging freeze thaw cycle occurs when the concrete has a high moisture level and a temperature below freezing based on that moisture content. These temperatures are discussed in Section 1 in the previous chapter. Figure 3 shows where there is a difference between the freeze thaw cycles and the damaging freeze thaw cycles. In other words, figure 3 shows where the concrete freezes, but because the concrete is so dry, the freezing does not cause damage to the concrete. This shows the importance of understanding the moisture content when a freeze occurs. Figure 4 shows the variability of the damaging freeze thaw cycles in different regions. The data has been organized where the variability is high, medium, and low. This is also an indicator of where there is significant difference in either the moisture or the amount of freezing that occurs when comparing one winter season to another.



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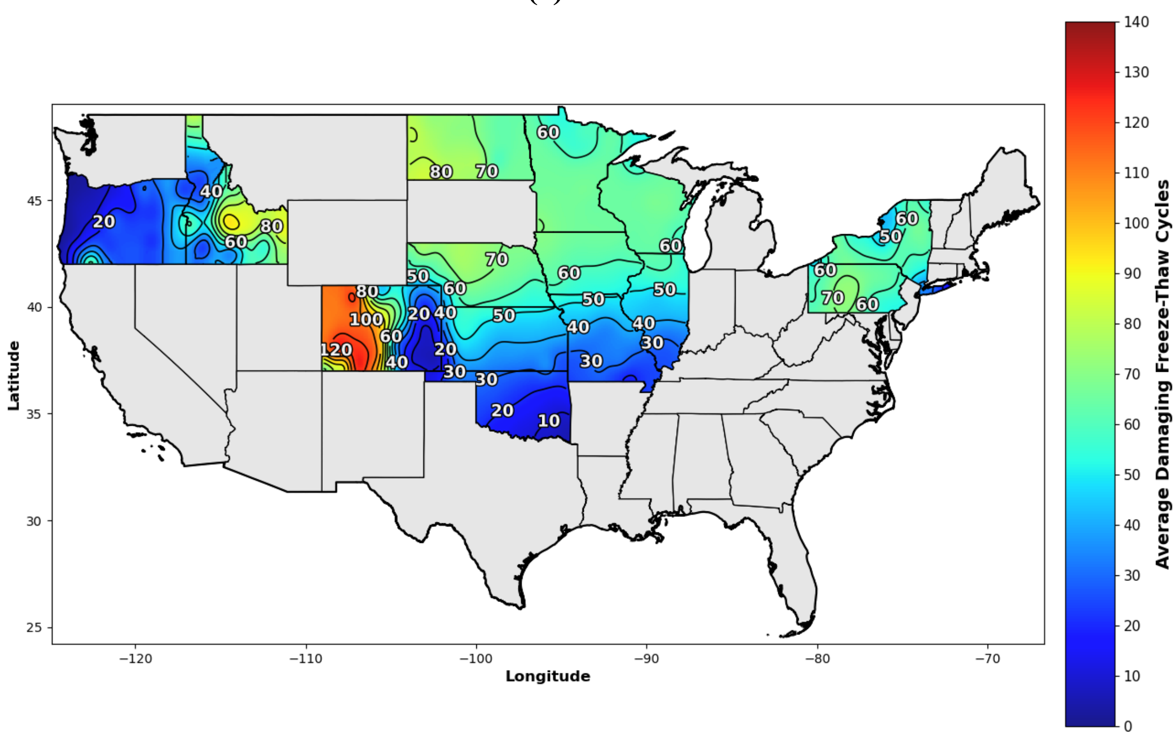


(b)

Figure 2: 24-Year average of predicted freeze–thaw cycles at all weather stations: (a) total freeze–thaw cycles, (b) damaging freeze–thaw cycles.

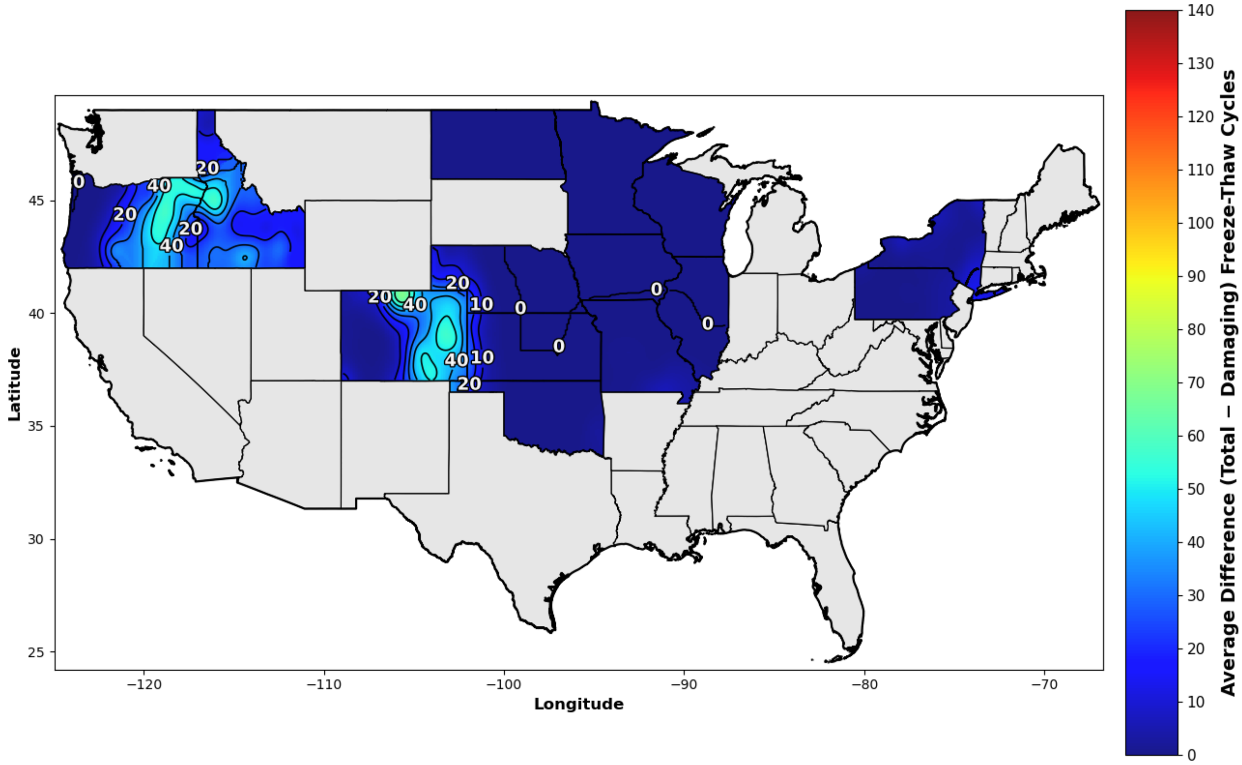


Figure 3: Average difference between total and damaging freeze–thaw cycles.

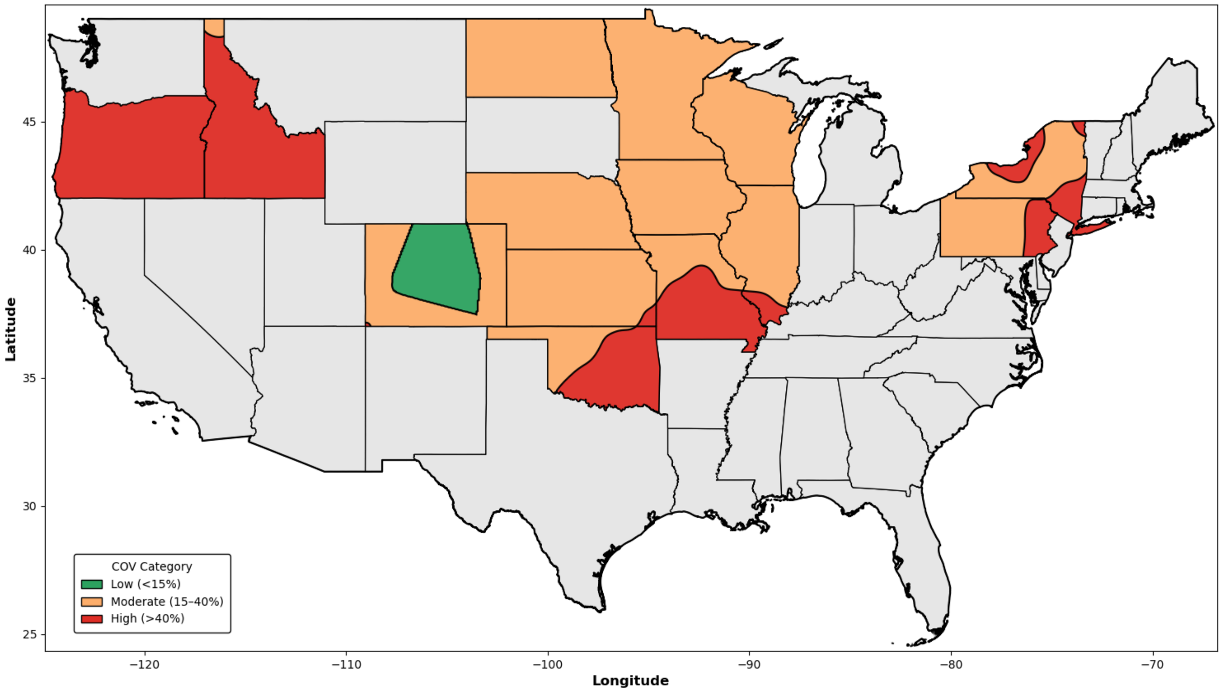


Figure 4: 24-Year spatial categories of CV (%) of predicted damaging freeze–thaw cycles at all weather stations.

4. Comparison with Existing Standards

The map of damaging freeze thaw cycles is compared to the LTPP Climate Classification in Figure 5. The LTPP simplifies the country into zones (e.g., Wet-Freeze, Dry-Freeze) but fails to capture the complexity of the DOS and the temperature fluctuations that create damaging freeze thaw cycles. The contour map provides conflicting recommendations to the LTPP map. For example, the LTPP treats the northeast part of the United States as a single climate zone titled “Wet-Freeze”. The contours show that there are regions with as low as 30 damaging freeze thaw c.ycles and as high as 70. For the northwest part of the United States the LTPP calls this region “Dry-Freeze”. This region has damaging freeze thaw cycles from 20 up to 120. While there are some locations that are dry and this decreases the number of damaging freeze thaw cycles, there are also locations that are quite wet and experience high freeze thaw cycles. This is especially true in Colorado and Idaho near the mountains.

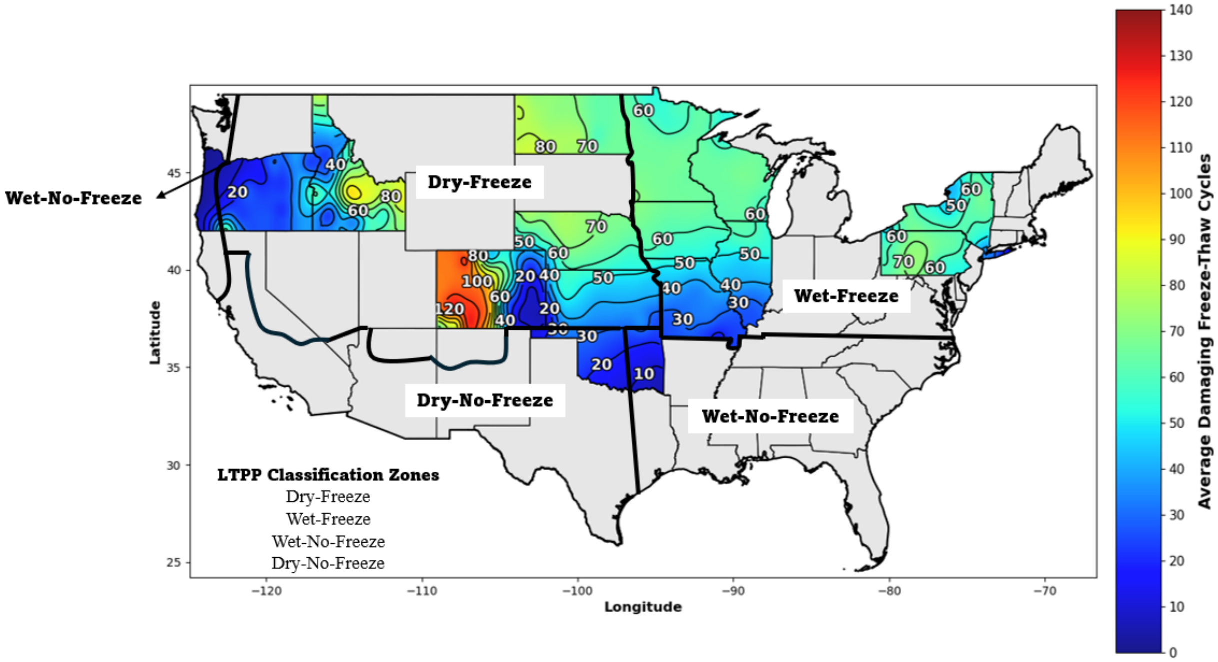


Figure 5: Overlay of LTPP climate zones with the 24-year average damaging freeze–thaw cycles.

The field-validated, DOS-based map seems to provide a more realistic and reliable assessment of freeze-thaw exposure relevant to concrete durability, offering specific cycle counts that LTPP does not.

5. Conclusion

The maps produced give practicing engineers tools to determine the amount of damaging freeze thaw cycles that their concrete is exposed to, instead of relying on engineering judgment.

- The maps provide an objective, long-term dataset to quantify the average number of damaging freeze-thaw cycles that concrete needs to withstand at any given location.
- This work also captures the variability of the damaging freeze thaw cycles. This allows the design to incorporate a safety margin determined by the variability of the weather and allows the design to be made for the worst-case winters instead of designing for the average.

This procedure provides a scalable, field-validated, and data-driven tool that directly quantifies the actual freeze-thaw damage potential for specific locations, moving concrete durability design from broad climate assumptions to precise, performance-based specification.

Toward a Specification for Air Based on Exposure Conditions

1. Introduction

This work discusses the potential of using degree-of-saturation (DOS) maps for developing geographically appropriate specifications for air content or related air parameters that consider exposure. This work is based on critical saturation theory. Critical saturation theory states that concrete will reach a limit state and begin to crack when it reaches a specific degree of saturation. This is called the critical degree of saturation, DOS_{CR} (Fagerlund 1975, Li et al, 2011, AASHTO R101).

2. Relating the Critical Degree of Saturation to Air Void Quality

When the concrete is critically saturated, freezing causes damage through cracking. The critical degree of saturation has been suggested to range from 72 to 91% depending on the mixture composition, likely a combination of the permeability of the matrix and the volume, size, and spacing of the air voids. The critical degree of saturation has been evaluated using several techniques (Todak et al. 2015b); however, this chapter will rely on results from length change of samples as they freeze (Ghantous et al. 2019a). Ghantous and Weiss (2019) demonstrated that lower water-to cement ratio (w/c) mixtures tended to have a slightly higher DOS_{CR} although this may be in the range of experimental variability (w/c = 0.35 – 89.5%, w/c = 0.45 – 86.7%, w/c = 0.55 - 87.8%). While the DOS_{CR} was similar, the rate of damage increased with w/cm. When the w/cm was 0.45 the rate of damage was 1.5x times greater than when the w/cm was 0.35. Also, when the w/cm was 0.55, the rate of damage was double that of the w/cm = 0.35.

Other work showed that systems with a higher quality air void system as measured by the SAM also had a higher DOS_{CR}. Figure 1 shows the probability of damage versus the degree of saturation (Ghantous et al 2021). Irrespective of the quality of the air void system, all samples with a DOS > 88% developed FT damage. Similarly, all samples with a DOS < 72.5% did not develop damage. When the DOS of the concrete is between 72.5% and 88%, the probability of freeze thaw damage is higher for samples with a SAM number > 0.20 (coarse air void system) than it is for the samples with a SAM number ≤ 0.20 (i.e., a higher quality air void system).

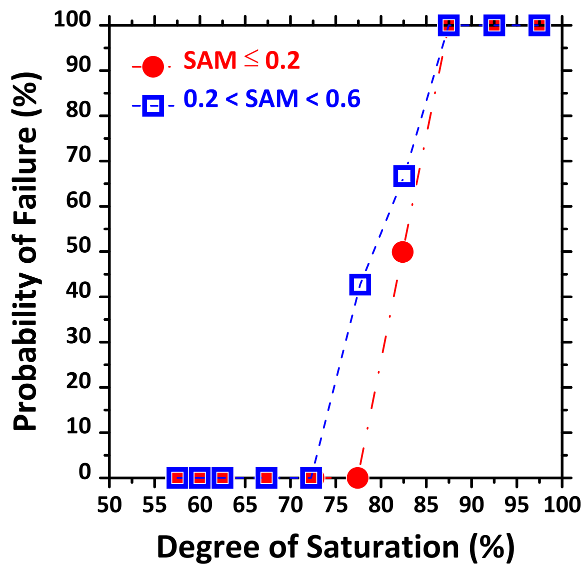


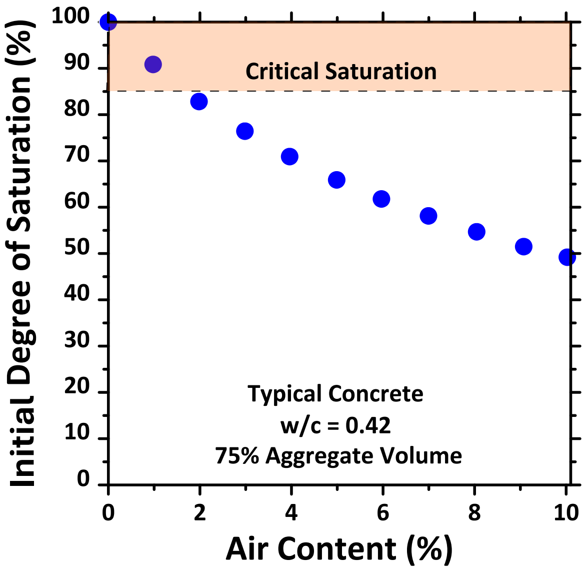
Figure 1: The Probability of Failure as a Function of Degree of Saturation for 134 samples (after Ghantous et al. 2021)

3. Relating the Air Content to the Time to Reach the Critical Degree of Saturation

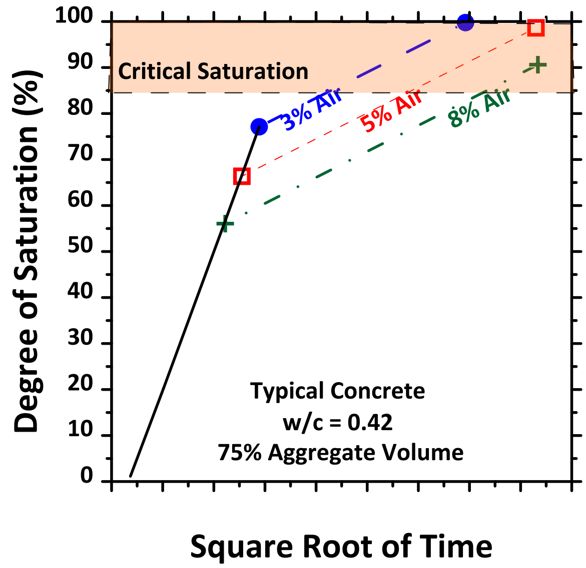
Figure 2a illustrates the initial degree of saturation or the matrix saturation of the concrete if there is no moisture lost after placement (after Todak et al. 2015a). The figure shows the results for a mixture with a w/cm of 0.42 and a 75% aggregate volume. This means that the remaining volume of material is composed of paste and air. As the air content increases, the initial degree of saturation decreases. This occurs because the entrained air voids do not fill with water unless there is prolonged exposure to water (Todak et al. 2015a).

Figure 2b shows how a sample absorbs water when it is in contact with water. The vertical axis is the DOS of the sample, and the horizontal axis is the square root of time. The solid line in Figure 2b shows that the sample begins to saturate as a function of the square root of time. This line starts with a sharp initial slope until the initial degree of saturation is reached. This value corresponds to the initial degree of saturation from Figure 2a. This initial degree of saturation can happen as quickly as a few days. After the matrix is saturated, the air voids begin to saturate. This process happens at a slower rate and so the slope of the line reduces, as shown by the dashed line in Figure 2b (Li et al. 2011). This means that concrete with a higher air content has a lower initial degree of saturation and this increases the time for the concrete to reach the critical degree of saturation. This will correspond to a longer service life.

When considering mixtures with typical concrete air contents, Figure 2a shows that an increase in air content of 1% will increase will decrease the DOS of the initial matrix saturation by 5% (based on a fitted line between air contents of 4 and 8%).



(a)



(b)

Figure 2: a) An Illustration of the Degree of Initial Degree of Saturation of Concrete for Varying Air Content (After Todak et al. 2015a,b) and b) the change in the degree of saturation with time where the black solid line shows the rapid saturation up to the initial degree of saturation from Figure 2a and the dashed lines show air void filling. (after Li et al. 2011, Moradllo et al. 2020)

4. Relating the Air Quality to the Critical Degree of Saturation and Durability

Another insight that one may want to draw is the role of air void quality. It has been previously shared by Weiss et al. (2016) that the critical degree of saturation that corresponds to freeze thaw damage is dependent on the quality of the air void system. As explained in section 2, a poor-quality air void system may have a lower critical DOS while a high-quality air void system would have a higher critical DOS.

Figure 3 shows data for two different concrete mixtures. For each mixture, the air void content and quality (as measured by the SAM air number) are related (Weiss et al. 2018). For mixture A (a higher quality air void system), satisfactory freeze thaw performance (as assessed by ASTM C666) is achieved with an air content of 3.5%, while mixture B (a lower quality air void system) requires an air content in excess of 6% for satisfactory freeze thaw performance (Figure 3b). This can also be demonstrated by the observation that mixture A has a SAM number of 0.20 at 3.7% air content, while for mixture B that 6.7% air content is required to reach the same SAM number. This corresponds reasonably well to the ASTM C666 durability factor in Figure 3b.

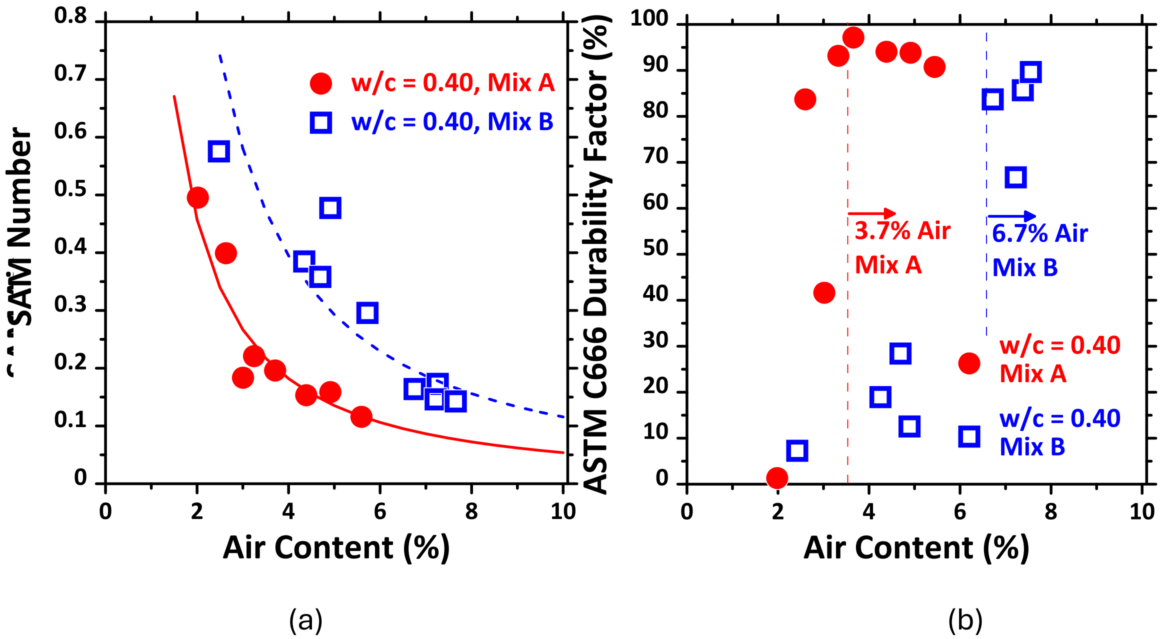


Figure 3: The relationship between the SAM number versus the volume of air content for two mixtures and b) the durability factor versus air content for two mixtures. (After Weiss et al. 2018)

5. Geographic Information

Geographic locations have different weather patterns that create different levels of DOS. Locations with a higher DOS will have a higher chance of reaching the critical saturation level of the concrete. Maps were developed as a part of this project that give the degree of saturation for various geographic locations based on field measurements and a machine learning model. Figure 4 shows an example of plot of the average DOS for different locations over a 24-year period. This DOS measurement is based on concrete with poor drainage and a low air content. It can be noticed that the DOS is greater in some states than others. For example, if comparing the state of Wisconsin and the state of Missouri. The DOS of Wisconsin is approximately 92.5% while the DOS of Missouri is approximately 85.0%. This is a DOS difference of 7.5%. This information can be used as a first estimate for the amount of air content needed in the concrete. Based on Figure 2a, a 1% increase in air content will decrease the initial matrix saturation by 5% as discussed in section 3. This would suggest that the specified air content in Wisconsin needs to be 1.5% greater than that of Missouri to have similar performance.

By using the same relationship between air content and initial matrix saturation, Figure 5 shows the target air content needed in a concrete mixture based on the measured DOS. This assumes that locations with a DOS of 85% would require 6% air to have satisfactory performance. Several states have a higher DOS (e.g., ND, NM, WI, NY, PA, IA) than other states and would benefit from a higher specified air content and there are other regions that can use a lower air content (e.g. parts of CO, OK, and OR).

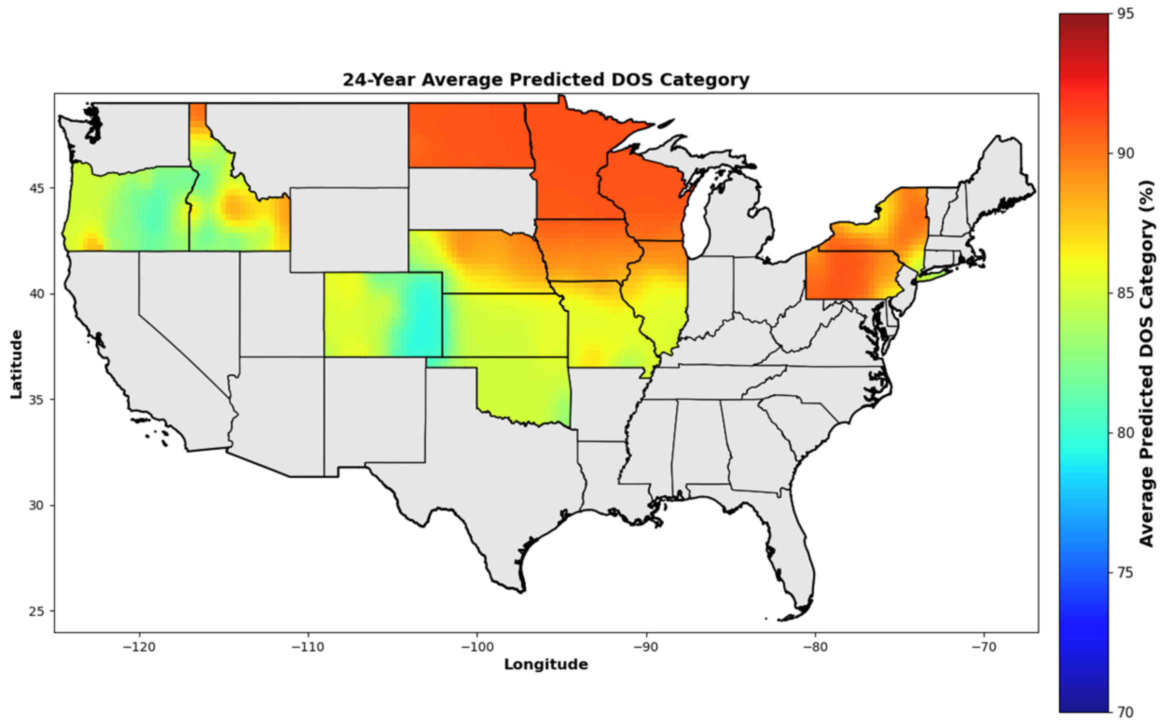


Figure 4: Predicted Degree of Saturation (DOS) based on the weather blocks and the machine learning models.

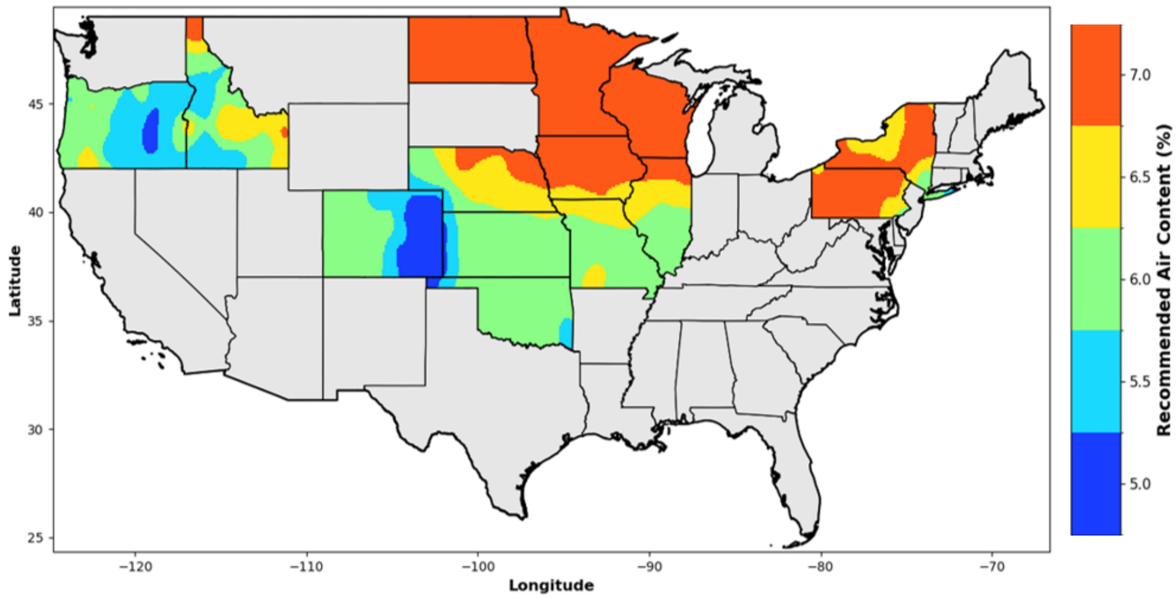


Figure 5: Recommended Target Air Content based on the predicted DOS.

6. Number of Damaging Freeze-Thaw Cycles

A damaging freeze-thaw cycle is defined as a freezing event that occurs when the concrete is above the critical DOS. Figure 6 shows the average number of damaging freeze-thaw cycles per year based on the average over the last 24 years. This map gives insight into the rate at which the concrete deteriorates once it reaches the critical DOS.

At this time, it is not well understood how freeze-thaw damage propagates after a concrete is critically saturated. In other words, how many freeze-thaw cycles can concrete resist after it is critically saturated before it is severely damaged? However, as concrete is wet and undergoes freeze-thaw cycles the chance that damage happens increases as the freezing will cause more of the pores to fill with water and it will test the ability of the concrete matrix to withstand the freezing. This means that places that have a high DOS and undergo a large number of freeze thaw cycles have the highest risk of damage.

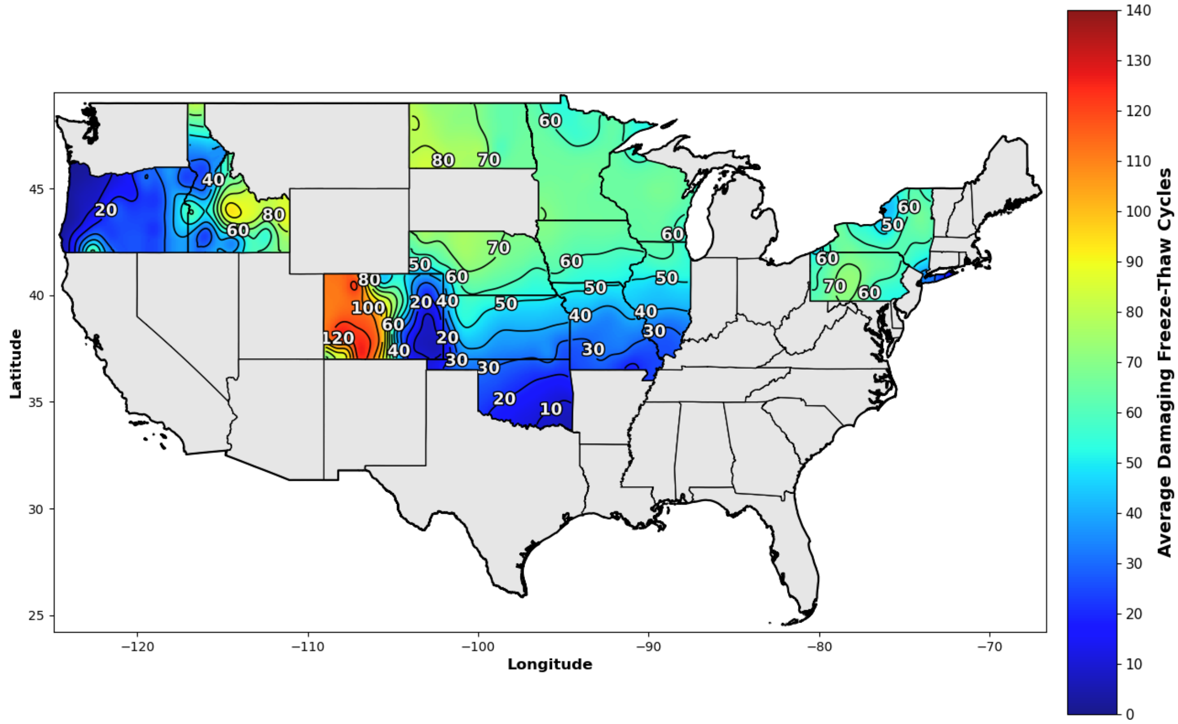


Figure 6: Average number of predicted damaging freeze-thaw cycles.

7. Conclusions

This work discusses using the degree-of-saturation (DOS) maps to develop geographically appropriate specifications for air content or related air parameters based on exposure. The following observations are made:

- A poor-quality air void system may have a lower critical DOS (DOS_{CR}) while a high-quality air void system would have a higher critical DOS (DOS_{CR}). This impacts the expected freeze-thaw service life of the concrete.
- For samples at the same DOS, the probability of freezing and thawing damage is more serious when the SAM number > 0.20, as compared to samples when the SAM number ≤ 0.20.
- As the air content increases, the initial matrix saturation decreases. An increase in air content of 1% will decrease the DOS by approximately 5%.
- The DOS is greater in some states than others (i.e., the concrete is more 'wet'). This corresponds to a need for a higher air content for similar life cycle performance.
- Maps of different DOS and the corresponding suggested air content are shown in Figures 4 and 5.

- The number of damaging freeze cycles, as shown in Figure 6, is an indication of the risk of damage once the concrete reaches the critical DOS.

More work is needed to understand how the damage propagates in the concrete once it reaches the critical DOS. Once this information is well understood, it can be used to predict the freeze-thaw service life of concrete.

8. Specification Recommendations

Based on this work, the following is recommended to be implemented into freeze thaw specifications:

1. Use the SAM or a hardened air void analysis in the mixture design stage to ensure the concrete provides a high-quality air void system. The recommended values are a SAM number ≤ 0.20 or a spacing factor ≤ 0.008".
2. Use Figure 5 to determine the target air content for your concrete. This map is based on the average DOS of the concrete. Allow the typical variation in air content of +/- 1% air.

With additional work to understand how damage propagates, the number of damaging freeze thaw cycles as shown in Figure 6 can be used to predict the risk of freeze thaw damage.

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The Effects of Concrete Temperature on Air Void Parameters in Pumped Concrete

1. Introduction

This document presents a comprehensive study on how pumping concrete, especially at varying temperatures, affects its air void system. The research aimed to determine the impact of pumping on air content, Super Air Meter (SAM) Number, spacing factor, and ultimately, freeze-thaw performance. The study is particularly relevant for those of us working in cold climates where freeze-thaw durability is a critical design consideration. The primary finding is that while pumping causes a temporary change in the air void system, it does not negatively impact the long-term freeze-thaw durability of concrete that was properly air-entrained before pumping.

Previous research showed that when pumping air-entrained concrete, the pressure during pumping causes the dissolution of smaller air bubbles [1-4]. Lab and field measurements show that these pressures regularly decrease the air content between 0.5% to 3%, occasionally observing larger losses, and at times even increases in the air volume [1, 5-7]. The previous research showed that the dissolved air bubbles will return to the concrete with a similar air void size distribution as measured by the spacing factor prior to pumping [8,9]. This observation is also supported by satisfactory freeze-thaw performance and observations of improved bubble spacing over time as measured by the SAM Number. However, most of the previous research was done in a lab environment with controlled temperature. This work aims to extend this by making concrete with different temperatures and determining if the temperature impacts the return of the air voids within the concrete.

2. Experimental Setup

The researchers used a Putzmeister TK 50 concrete pump and a standard pipe network for the laboratory testing. The setup allowed for continuous concrete flow, with the pumped concrete being returned to the hopper to simulate a single pumping cycle.

The study tested concrete mixtures at three different temperatures to represent field conditions: cold (8∘C/46∘F), room temperature (30∘C/86∘F), and hot (40∘C/104∘F). To ensure a consistent mixture design, fly ash was used as a 20% mass replacement for cement, and citric acid was added to delay the set time, which isolated the effects of pumping from those of concrete hydration.

Measurements of slump, unit weight, air content (using the SAM), and SAM Number were taken at various intervals: before pumping, immediately after pumping, and every 25 minutes for up to 120 minutes. Freeze-thaw resistance (ASTM C666) and hardened air void analysis (ASTM C457) were conducted on samples taken before pumping, immediately after pumping, and 120 minutes after pumping.

3. Key Findings

3.1 Air Content Loss:

A summary of the air content measurements before and after the pump are shown in Table 1. Pumping caused a significant reduction in air content across all temperature ranges, with a loss of at least 20% of the initial air volume. However, the air loss was not uniform. The cold mixtures experienced a significantly higher air loss (an average of 2.3% or 40% normalized loss) compared to the room temperature and hot mixtures (average loss of 1.4% to 1.7% or 20% to 25% normalized loss). This suggests that cold concrete is more susceptible to air loss during pumping.

Table 1

Average and Standard Deviation of Fresh Concrete Air Content%.

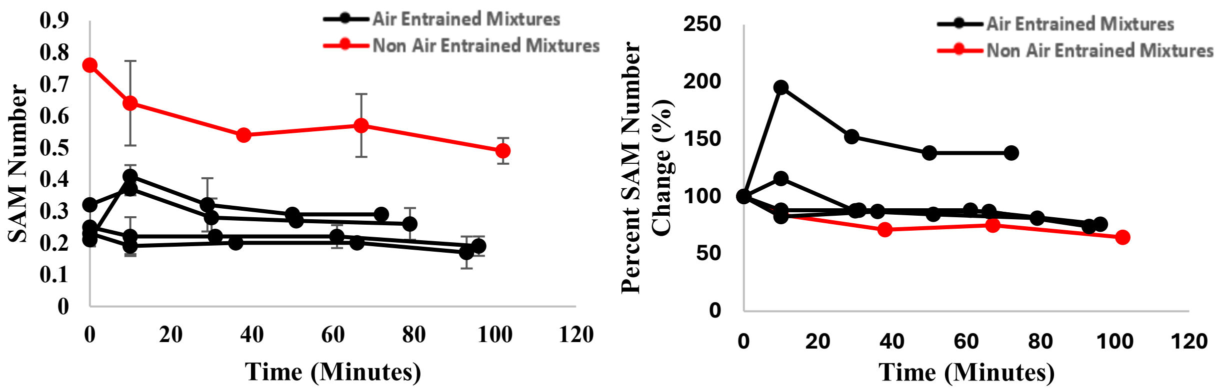
Mixtures	Average Air% of Fresh Concrete (%)		Average Air loss (%)	Percentage Loss of Air Content After Pumping (%)	Standard Deviation of Fresh Concrete Air Content %	
	Before Pumping	Immediately after Pumping		(Avg Air Loss/Air Before Pumping x 100)	Before Pumping	Immediately after Pumping
Room Temperature	6.9	5.5	1.4	20	0.98	0.78
Hot	6.8	5.1	1.7	25	1.08	0.57
Cold	5.7	3.4	2.3	40	0.45	0.36

3.2 The Re-formation of Air Voids

The SAM Number, a measure of the quality of the air void system, generally increased immediately after pumping and then decreased over time. A plot for the hot concrete is shown in Figure 1. Other figures are included in Volume II of this report. This indicates that the smaller, higher internal pressure air bubbles that were dissolved under pressure are re-forming in the concrete.

For the room temperature and hot mixtures, the SAM Number returned to a value close to its original value within the 120-minute test period. This aligns with the theory that the air bubbles return to the concrete with a similar distribution as before.

However, for the cold mixtures, the SAM Number did not return to its original value even after 120 minutes. This is likely due to the slower rate of gas diffusion at lower temperatures, which delays the re-formation of the air voids. The extended set time of the cold concrete would allow for more time for the voids to re-form before the concrete hardens.



a) SAM Number vs. Time. b) Normalized SAM Number.

Figure 1. SAM Number vs. Time Before and After Pumping of (40°C/104°F) Concrete Mixtures.

3.3 Hardened Concrete Properties

The study found no statistically significant change in the spacing factor, as measured by ASTM C457. All measurements fell within the expected variation of the test method. This reinforces the idea that the changes in the air void system in the fresh concrete do not have a lasting effect on the air void system in the hardened concrete.

3.4 Freeze-Thaw Performance

The most critical finding is that satisfactory freeze-thaw performance was consistently observed in concrete mixtures that had an initial air content greater than 4% and an initial SAM Number less than 0.32, regardless of the changes caused by pumping or the concrete's temperature. This demonstrates that the air content and SAM Number measurements taken immediately after pumping may not be a reliable indicator of the concrete's ultimate freeze-thaw durability. This matches previous research done in the lab and the field of Part 1 of this project.

4. Practical Implications

Based on these findings, the study suggests two practical solutions:

1. Only test the air content and SAM Number of the concrete mixture before it goes into the pump. The conventional limits for air content and SAM Number for un-pumped concrete (4% air content, SAM Number < 0.32) are reliable indicators of freeze-thaw durability in the final hardened concrete.

2. If testing is done after pumping, wait for the air void system to recover. However, this is not a practical solution in the field due to the variability in recovery time, especially for cold mixtures.

In summary, the research confirms that while pumping temporarily modifies the air void system in fresh concrete, it does not significantly harm the long-term freeze-thaw resistance of properly air-entrained concrete. The air bubbles that are dissolved under pressure re-form before the concrete hardens, resulting in a durable air void system. This provides a strong case for not rejecting concrete based on post-pumping air void measurements if the initial mix met the specifications for the air void system.

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