**TRANSPORTATION POOLED FUND PROGRAM**

**QUARTERLY PROGRESS REPORT**

Lead Agency (FHWA or State DOT): Oklahoma Department of Transportation

**INSTRUCTIONS:**

*Project Managers and/or research project investigators should complete a quarterly progress report for each calendar quarter during which the projects are active. Please provide a project schedule status of the research activities tied to each task that is defined in the proposal; a percentage completion of each task; a concise discussion (2 or 3 sentences) of the current status, including accomplishments and problems encountered, if any. List all tasks, even if no work was done during this period.*

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| **Transportation Pooled Fund Program Project #***TPF-5(448)* | **Transportation Pooled Fund Program - Report Period:**O Quarter 1 (January 1 – March 31)O Quarter 2 (April 1 – June 30)X Quarter 3 (July 1 – September 30)O Quarter 4 (October 1 – December 31) |
| **Project Title:****Integrating Construction Practices and Weather Into Freeze Thaw Specifications** |
| **Name of Project Manager(s):****Tyler Ley** | **Phone Number:****405-744-5257** | **E-Mail**Tyler.ley@okstate.edu |
| **Lead Agency Project ID:****TPF-TPF5(448)** | **Other Project ID (i.e., contract #):**AA-1-501021 | **Project Start Date:**August 30, 2020 |
| **Original Project End Date:**August 30, 2023 | **Current Project End Date:****January 31, 2025**  | **Number of Extensions:**1 |

Project schedule status:

 X On schedule On revised schedule □ Ahead of schedule □ Behind schedule

Overall Project Statistics:

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|  **Total Project Budget** |  **Total Cost to Date for Project** |  **Percentage of Work**  **Completed to Date** |
| $910,000 | $780,000 | 92% |

***Quarterly*** Project Statistics:

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|  **Total Project Expenses**  **and Percentage This Quarter** |  **Total Amount of Funds**  **Expended This Quarter** |  **Total Percentage of**  **Time Used to Date** |
| 9% | $65,000 | 94% |

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| **Project Description**:Concrete can be damaged when it is:1) sufficiently wet (has reached a critical degree of saturation) and 2) is exposed to temperature cycles that enable freezing and thawing. The damage that occurs due to freezing and thawing can lead to premature deterioration, costly repairs, and premature replacement of concrete infrastructure elements. Current specifications for frost durability are largely based on work completed in the 1950s, and while this work included many landmark discoveries (Kleiger 1952, 1954). This work from the 1950s may not be representative of materials used in modern concrete mixtures. The objective of this work is to build on previous research efforts to produce improved specifications and advance existing test methods; while, improve the underlying understanding of freeze thaw damage. This work will specifically focus on construction practices and the impact of weather.The objectives are: 1. Quantify how different weather conditions impact the freeze thaw performance of concrete with low-cost data loggers. This work has been started under this existing project but these samples should be distributed in the field and used to quantify the combination of saturation and freeze thaw cycles in different states.
2. Investigate the freeze thaw performance of existing structures in different climates with different air void qualities. In combination with quantifying the weather in different environments, structures should be found in these structures with different quality of air void systems to determine how they perform. This will provide true case studies of field performance in a quantified exposure.
3. Expand the freeze thaw model to a larger range of mixtures to see if the trends still hold.
4. Further evaluation of the accuracy of the modeling predictions for determining the matrix saturation and the relationship between the secondary sorption and formation factor.
5. Better understand the damage propagation after critical saturation is reached.
6. Extension of this work to include salts such as those that result in calcium oxychloride to further improve the computational modeling predictions.
7. Determine how air void filling impacts the durability of concrete from freeze thaw cycles.
8. Develop freeze thaw specifications based on concrete quality, air void system, and local weather conditions.
9. Determine how construction methods such as pumping, mixing time, paving vibration, and hand held vibrators impact the air void spacing within concrete
10. Improve the SAM by making the measurement more consistent through developing a semi-automated testing procedure and improving reliability prediction.
11. Further refine a rapid test method that measures the uptake and fluid and resistivity of the concrete to determine the freeze thaw durability of concrete
12. Complete more tests with pumped concrete to evaluate how the air voids return to the concrete over time.
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| **Progress this Quarter (includes meetings, work plan status, contract status, significant progress, etc.):**1. Quantify how different weather conditions impact the freeze thaw performance of concrete with low-cost data loggers. This work has been started under this existing project but these samples should be distributed in the field and used to quantify the combination of saturation and freeze thaw cycles in different states.

Data is continuing to be collected and analyzed. A paper has been written and published. The work focuses on Oklahoma weather. The group has extended this work to other states. This was shared with the state DOTs. The team has developed a machine learning model that can use weather to predict the number of damaging freeze thaw cycles in concrete. This shows great promise and seems to be quite accurate.The results show that the differences in performance between states are tied to the degree of saturation and the number of times the concrete freezes. Finalizing this work will be the focus of the research.A preliminary map of the number of damaging freeze thaw cycles is provided in Figure 1.A map of the united states  Description automatically generatedFigure 1 – The number of damaging freeze thaw cycles based on the machine learning prediction. Each circle is a weather station used for prediction. Dark blue means that there is more expected damage than white.1. Investigate the freeze thaw performance of existing structures in different climates with different air void qualities. In combination with quantifying the weather in different environments, structures should be found in these structures with different quality of air void systems to determine how they perform. This will provide true case studies of field performance in a quantified exposure.

Samples have been provided for this. This will be done in correspondence with task 1. 1. Expand the freeze thaw model to a larger range of mixtures to see if the trends still hold.

In part 1 of the project, researchers had developed a correlation between the probability of failure due to freeze-thaw cycles with respect to the degree of saturation of the mortar samples tested (Figure 1). This correlation in Figure 1 was collected on 134 samples prepared with cement type I/II and with different air void content and air void quality. Only 9 different mixtures were tested to obtain Figure 2. The research is expanding this plot by adding a number of samples from a much wider array of mixtures, especially mixtures containing SCM. The results have required some re-examination due to potential changes in the freezing processes of materials containing SCM. This work is underway and important to determine the volume of freezable water. This work is still ongoing.Figure 2. Probability of failure with respect to the degree of saturation [2] 1. Further evaluation of the accuracy of the modeling predictions for determining the matrix saturation and the relationship between the secondary sorption and formation factor.

In the previous part of the project, a correlation was established between the apparent formation factor and the initial and secondary sorptivity coefficient of plain concrete samples [5, 6]. The correlation is not established yet for concrete samples with supplementary cementitious materials. The apparent formation factor as well as the initial and secondary sorptivity of concrete samples with varying fly ash content has been tested in the second part or the project [7]. The mixture design of these concrete samples is given in Table 1. Table 1. The mixture proportions and fresh properties of the cementitious samples (normalized to 1000kg/m3)

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| Mixture | Coarse aggregate 1(kg/m3) | Coarse aggregate 2(kg/m3) | Sand (kg/m3) | Cement (kg/m3) | Fly ash(kg/m3) | Water (kg/m3) | AEA(g/m3) | Adva Cast 575(g/m3) | Air content (%),SAM number |
| 1 | 469.3 | 0.0 | 305.2 | 124.0 | 30.9 | 69.8 | 0.8 | 0.0 | 2.55, 0.350 |
| 2 | 468.4 | 0.0 | 304.6 | 123.8 | 30.9 | 69.6 | 2.7 | 0.0 | 5.40, 0.155 |
| 3 | 468.1 | 0.0 | 305.8 | 116.1 | 38.7 | 69.7 | 1.5 | 0.0 | 2.10, 0.660 |
| 4 | 466.1 | 0.0 | 304.4 | 115.6 | 38.5 | 69.4 | 6.0 | 0.0 | 7.15, 0.100 |
| 5 | 467.6 | 0.0 | 305.5 | 116.0 | 38.7 | 69.6 | 2.7 | 0.0 | 2.9, 0.200 |
| 6 | 468.1 | 0.0 | 305.8 | 108.5 | 46.5 | 69.8 | 1.3 | 0.0 | 1.80, 0.630 |
| 7 | 466.1 | 0.0 | 304.4 | 108.0 | 46.3 | 69.5 | 5.7 | 0.0 | 5.65, 0.130 |
| 8 | 467.5 | 0.0 | 305.4 | 108.4 | 46.4 | 69.7 | 2.6 | 0.0 | 3.2, 0.315 |
| 9 | 467.9 | 0.0 | 305.6 | 100.9 | 54.3 | 69.8 | 1.5 | 0.0 | 1.95, 0.545 |
| 10 | 465.8 | 0.0 | 304.3 | 100.4 | 54.1 | 69.5 | 5.9 | 0.0 | 7.10, 0.100 |
| 11 | 467.4 | 0.0 | 305.3 | 100.8 | 54.3 | 69.8 | 2.6 | 0.0 | 2.7, 0.24 |
| 12 | 469.5 | 0.0 | 304.5 | 93.1 | 61.9 | 69.8 | 1.1 | 0.0 | 2.55, 0.570 |
| 13 | 468.6 | 0.0 | 303.9 | 93.0 | 61.8 | 69.7 | 3.1 | 0.0 | 5.85,0.100 |
| 14 | 262.2 | 202.3 | 312.2 | 112.7 | 28.2 | 63.4 | 1.1 | 18.0 | 5.75, 0.24 |
| 15 | 261.9 | 202.0 | 311.8 | 112.5 | 28.1 | 63.3 | 2.2 | 18.0 | 8.5, 0.065 |
| 16 | 262.5 | 202.5 | 312.5 | 112.8 | 28.2 | 63.5 | 0.7 | 17.3 | 3.6, 0.505 |
| 17 | 260.4 | 202.9 | 313.0 | 105.9 | 35.3 | 63.6 | 0.7 | 18.1 | 4.9, 0.4 |
| 18 | 260.2 | 202.7 | 312.7 | 105.8 | 35.3 | 63.5 | 1.7 | 18.2 | 7.3, 0.115 |
| 19 | 259.3 | 203.0 | 313.2 | 98.9 | 42.4 | 63.6 | 1.6 | 18.0 | 5.6, 0.17 |
| 20 | 259.7 | 203.2 | 313.6 | 99.0 | 42.4 | 63.7 | 0.8 | 17.6 | 4.150.395 |
| 21 | 259.8 | 202.1 | 313.8 | 92.0 | 49.5 | 63.7 | 1.8 | 17.4 | 5.40.18 |
| 22 | 259.4 | 201.8 | 313.3 | 91.9 | 49.5 | 63.6 | 1.5 | 18.9 | 4.3, 0.38 |
| 23 | 259.0 | 202.4 | 314.3 | 85.1 | 56.7 | 63.8 | 0.7 | 17.9 | 2.75, 0.5 |
| 24 | 258.6 | 202.1 | 313.9 | 85.0 | 56.6 | 63.7 | 2.3 | 17.7 | 6.5, 0.21 |
| 25 | 258.7 | 202.2 | 314.0 | 85.0 | 56.7 | 63.7 | 1.8 | 18.0 | 4.65, 0.325 |

The apparent formation factor measurements have been performed using two concrete samples from each mixture design. For this measurement, the uniaxial resistance was measured using AASHTO TP 119 [8] after 7 and 14 days of immersion in the simulated pore solution (Option A). After the different duration of immersion, the resistance was measured along with temperature, and sample geometry. The resistivity of the specimen was calculated using equation 1.

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| $$ρ\_{s}=R⋅\frac{A}{L}$$ | 1 |

Where, $ρ\_{s} $is theresistivity of specimen, $R$ is the resistance of the specimen (Ω), $A$ is specimen cross-sectional area (m2), $L$ = average specimen length (m). Temperature corrections were made using the Arrhenius approach following the guidance of Coyle et al. [9] with an activation energy of 15 kJ/mol.The formation factor was calculated using equation 2

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| $$F=\frac{ρ\_{s}}{ρ\_{ps}}$$ | 2 |

Where, the resistivity of the simulated pore solution (𝜌𝑝s) was equal to 0.127 Ω.mFor the absorption test, from one of these concrete samples, 3 slices of 2 inches thickness each were cut from the middle section of the sample and were put at 50% RH environment and 23°C in order to reach equilibrium. The testing is complete and being analyzed. 1. Better understand the damage propagation after critical saturation is reached.

X-ray computed tomography has been used to examine damage from CaOXY. The results show that crack propagation and void filling occurs from CaOXY. The CT work can quantify the change in the crack size over time and also how the air voids fill from CaOXY. This helps to bench mark and quantify these important changes that are occurring and provide new levels of insight. The work also shows that with high fly ash replacement that there is no damage observed. The paper is being completed and should be submitted soon.1. Extension of this work to include salts such as those that result in calcium oxychloride to further improve the computational modeling predictions.

In the first part of the project, researchers have studied the salt damage that developed in mortar samples due to the formation of calcium oxychloride. Mortar samples with varying air content, varying air void quality and varying fly ash content were saturated in 20% calcium chloride (CaCl2) solution. Micro X-ray fluorescent spectroscopy was used to determine that the chloride ions were uniformly distributed throughout the sample. Saturated samples were exposed to temperature cycles varying from 50°C to 5°C while being immersed in 20% CaCL2 solution. During the cooling period, calcium oxychloride (CaOXY) develops in the pores of the mortar samples. During the heating period, CaOXY melts. CaOXY is a product of the reaction between CaCl2 and calcium hydroxide. The volume of CaOXY is smaller than the reactants. Consequently, during the cooling period, due to the volume shrinkage induced by CaOXY formation, 20% CaCl2 solution can diffuse and refill the pores of the cementitious materials. During the heating process, CaOXY melts and expand in volume leading thus to internal pressure and salt damage. The length of the sample was measured at the beginning and end of each temperature cycle using a high precision micrometer. When a sample is damaged, an increase in its length will be measured. The residual strain was used as an indicator for damage and was calculated according to equation 1.

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|  | $$Residual strain= \frac{l\_{i}-l\_{0}}{l\_{0}}$$ | (1) |

Where, l0 is the initial length of the sample, li is the length of the sample after each temperature cycle. The data collected show that * Higher fly ash content mixtures (35% and 40%) did not develop damage regardless of the air void content. This can be explained by the fact that the calcium hydroxide content is not high enough to generate sufficient CaOXY to lead to damage [10-12].
* Lower fly ash content mixtures (0-20%) developed salt damage irrespective of the air void content. This is because the calcium hydroxide content is high enough that a volume of CaOXY exceeds the air void volume resulting in damage.
* Intermediate fly ash content mixtures (25% and 30%) demonstrated that samples with higher air content had improved resistance to salt damage (compared to those with a lower entrained air content). This can be explained by the difference in the available space that the air voids provide for CaOXY to form.
* The absorption of the fluid by the samples during temperature cycling has a significant impact on increasing salt damage development

The paper has been completed and the work has been published.1. Determine how air void filling impacts the durability of concrete from salt damage.

X-ray CT scans will be conducted to measure the filling of voids due to CaOXY (formation and melting). The measurements obtained from X-ray CT will be compared with the volume of calcium oxychloride measurements using the LT-DSC The CT scans are being completed and air void filling is being observed. This shows that this is an important mechanism in the deterioration of concrete. This is discussed in more detail in work item 5.1. Develop freeze thaw specifications based on concrete quality, air void system, and local weather conditions.’

The team has developed data on concrete quality and air void quality. The final step is to look at local weather conditions. This work is still underway. 1. Determine how construction methods such as pumping, mixing time, paving vibration, and hand held vibrators impact the air void spacing within concrete

Efforts have been completed to look at vibration and drop height. Much of this work is in the process of being published. 1. Improve the SAM by making the measurement more consistent through developing a semi-automated testing procedure and improving reliability prediction.

Improvements have been made in the Bluetooth SAM gauge and now the test is running properly. These gauges have been shared with the DOTs so that they can be used in the next construction season. The team had a call with the states to introduct the new gauge and receive feedback. There were some issues with a few of the phones and the team is working to address this.Based on user feedback a removable pressure gauge has been developed. This will allow the user to remove the gauge from the SAM and protect it. This should reduce damaged gages in the field and make the meter more robust. A water proof carrying case has also been developed to transport the gauge.An automated SAM is working well. A local company is producing a field version of the test. 1. Further refine a rapid test method that measures the uptake and fluid and resistivity of the concrete to determine the freeze thaw durability of concrete

The authors believe that this is a critical finding from the paper on CaOXY formation and damage. The work has examined that the absorption of water was key for both FT and CAOXY damage. Earlier work had examined the role of temperature on water absorption and pumping. The research team is trying to examine whether this could be incorporated into a testing procedure to more rapidly assess water absorption and saturation. The work is progressing and will be a primary component of the work moving forward.1. Complete more tests with pumped concrete to evaluate how the air voids return to the concrete over time.

FHWA has funded additional research to investigate how air voids are lost during pumping and how those air voids return to the fresh concrete before it is hardened. The testing has been completed except for some freeze thaw tests that are still ongoing. Concrete was created with temperatures of 73F, 95F, and 40F and then tested before and after pumping. This paper has beed submitted. **References:** 1. Ghantous, R.M. and J. Weiss, Does the water to cement ration= of concrete impact the value of its critical degree of saturation? , in 10th Inter national 14 Conference on Fracture Mechanics of Concrete and Concrete Structures. 2019: Bayonne, France. p. 1-10.2. Ghantous, R.M., et al., Determining the freeze-thaw performance of mortar samples using length change measurements during freezing. accepted in cement and concrete composite 2020.3. Ley, M.T., et al., Determining the air-void distribution in fresh concrete with the Sequential Air Method. Construction and Building Materials, 2017. **150**: p. 723-737.4. Todak, H.N., Durability assessments of concrete using electrical properties and acoustic emission testing, in School of Civil Engineering. 2015, Purdue University: West Lafayette. p. 143.5. Khanzadeh Moradllo, M., et al., Quantifying fluid filling of the air voids in air entrained concrete using neutron radiography. Cement and Concrete Composites, 2019. **104**.6. Moradllo, M.K., et al., Relating the formation factor of concrete to water absorption. ACI Mater. J., 2018. **Submitted**.7. ASTM C1585-13 Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes. 2013, ASTM International: West Conshohocken, PA.8. AASHTO, Standard Method of Test for Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test, in TP 119-20. 2020, American Association of State Highway and Transportation Officials: Washington DC.9. Coyle, A.T., et al., Comparison of linear temperature corrections and activation energy temperature corrections for electrical resistivity measurements of concrete. Advances in Civil Engineering Materials, 2018. **7**(1): p. 174-187.10. Suraneni, P., et al., Use of fly ash to minimize deicing salt damage in concrete pavements. Journal of the Transportation Research Board, 2017. **2629**: p. 24-32.11. Suraneni, P., et al., Role of supplementary cementitious material type in the mitigation of calcium oxychloride formation in cementitious pastes. Journal of Materials in Civil Engineering, 2018. **30**: p. 1-10.12. Suraneni, P., et al., Calcium oxychloride formation potential in cementitious pastes exposed to blends of deicing salt. ACI Materials Journal, 2017. **114**(4): p. 631-641.13. Del Mar Arribas-Colón, M., et al., Investigation of Premature Distress Around Joints in PCC Pavements: Parts I & II. 2012, Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana: Publication FHWA/IN/JTRP-2012/25 & FHWA/IN/JTRP-2012/26.14. Jones, W., et al., An Overview of Joint Deterioration in Concrete Pavement: Mechanisms, Solution Properties, and Sealers. 2013: West Lafayette, Indiana.15. Castro, J., et al., Durability of saw-cut joints in plain cement concrete pavements. 2011, Purdue University. Joint Transportation Research Program.16. Graveen, C., et al., Performance Related Specifications (PRS) for Concrete Pavements in Indiana, Volume 2: Technical Report. 2009.17. Engineers, A.S.o.C. ASCE 2017 infrastructure report card. 2017.18. Olek, J., M. Radlinski, and M. del Mar Arribas. Premature deterioration of joints in selected Indiana portland cement concrete pavements. 2007.19. Suraneni, P. and J. Weiss, Extending Low-Temperature Differential Scanning Calorimetry from Paste to Mortar and Concrete to Quantify the Potential for Calcium Oxychloride Formation. Advances in Civil Engineering Materials, 2018. **7**(1): p. 1-16. |
| **Anticipated work next quarter**:Continue to work on each task. |

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| **Significant Results:**Calcium and magnesium deicing salts may damage concrete due to calcium oxychloride formation (CaOXY). Previous work has shown that replacing a portion of the cement in a mixture with supplementary cementitious materials reduce CaOXY formation. AASHTO PP-84 was developed to help specify damage-resistant mixtures by limiting the CaOXY amount in paste. This limit was established based on empirical observations; however, this did not consider other aspects of the mixture such as paste volume or air content. This paper investigates how fluid absorption, paste volume, and air content are all key parameters in determining damage from CaOXY. Concrete with a higher paste volume has more CaOXY and is more susceptible to damage. Concrete with a higher air content is less susceptible to damage as the voids provide space for fluid absorption and CaOXY formation; however this only occurs for mixtures with a specific range of calcium hydroxide (Ca(OH)2) (between 7 and 12 g Ca(OH)2/100 g paste). We have developed a comprehensive explanation for CaOXY-induced damage in concrete. https://doi.org/10.1016/j.cemconcomp.2022.104697 |
| **Circumstance affecting project or budget. (Please describe any challenges encountered or anticipated that** **might affect the completion of the project within the time, scope and fiscal constraints set forth in the agreement, along with recommended solutions to those problems).** |

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| **Potential Implementation:**  |