**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)  X Quarter 2 (April 1 – June 30)  O 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:**  **August 30,2023** | | **Number of Extensions:**  0 |

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** |
| $660,000 | $350,000 | 60% |

***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** |
| 5% | $25,000 | 50% |

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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 reviewed by the team. This paper has been submitted for publication. The work focuses on Oklahoma weather. The group is also working on extending this work to the other weather stations. One challenge is that because of the weather, some of the weather stations did not have continuous power and so they were not always in service. This makes it hard to compare the data between the different stations. The team plans on developing a model that can take the weather into account and predict the number of effective freeze thaw cycles in concrete. This is still being developed.   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 start later in the project. More projects are being sought for this.   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 mortar 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 1.    Figure 1. Probability of failure with respect to the degree of saturation [2]  The research is expanding this plot by adding a number of samples from a much wider array of mixtures. This helps validate the SAM and also the importance of freeze thaw durability. These samples are being prepared for analysis and they will be added to Figure 1. The bin size for the statistical analysis in Figure 1 is 5%. These additional measurements will allow decreasing the bin size to 2% which will give more confidence in the correlation and conclusion drawn out of this graph. Sample preparation continues for this work.     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 will be tested in the second part or the project [7]. The correlation will be determined for samples with fly ash and compared with the correlation obtained on plain concrete samples. This relationship provides a powerful tool in quality control to obtain *FAP* that relates to absorption properties by using a simple immersion test. The fluid absorption properties are key parameters in service life prediction of concrete structures subjected to freezing-and-thawing cycles.  Concrete samples with 25 different mixture design has been prepared. 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)   |  |  |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | | 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 | 4.15  0.395 | | 21 | 259.8 | 202.1 | 313.8 | 92.0 | 49.5 | 63.7 | 1.8 | 17.4 | 5.4  0.18 | | 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.   |  |  | | --- | --- | |  | 1 |   Where, is theresistivity of specimen, is the resistance of the specimen (Ω), is specimen cross-sectional area (m2), = 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   |  |  | | --- | --- | |  | 2 |   Where, the resistivity of the simulated pore solution (𝜌𝑝s) was equal to 0.127 Ω.m  For 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. Most of this testing is complete and the results are being compiled for presentation in the future.   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. A paper has been completed and it will be submitted soon. The research team is now thinking about how they could use additional techniques to learn more about the damage. This will be worked on after completing the field work in Task 1.   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.   |  |  |  | | --- | --- | --- | |  |  | (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 signifincant impact on increasing salt damage development   Work is underway to understand how the air void system distribution impacts the CaOXY damage. The preliminary work suggests that there is not much impact of the air void distribution but this is an area of future work.   1. Determine how air void filling impacts the durability of concrete from salt damage.   Differential scanning calorimetry (DSC) is an experimental technique in which the difference in the amount of heat required to increase the temperature of a sample compared to a reference is measured as a function of the temperature. This technique can be used to determine the phase change in the sample as well as quantity of material undergoing the phase change. A powder will be prepared from each mix design tested in task 6 (salt damage) and will be mixed with 20% CaCl2 solution at a ratio of 4:1 [19]. The CaOXY that develops will be quantified. The volume of calcium oxychloride will then be concluded.  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.   1. Develop freeze thaw specifications based on concrete quality, air void system, and local weather conditions.’   This will be done at the end of the project.   1. Determine how construction methods such as pumping, mixing time, paving vibration, and hand held vibrators impact the air void spacing within concrete   OK state is looking at vibration and how it impacts the air void system in concrete. Some of this is to improve the SAM and the accuracy with low slump concrete. Some of this is with field concrete and with different vibration. Testing was also done on concrete that free falls and then hits the ground. Both of these efforts are ongoing but some nice progress has been made. The drop height work has been completed and the data if being analyzed further.   1. Improve the SAM by making the measurement more consistent through developing a semi-automated testing procedure and improving reliability prediction.   The delays using the Bluetooth gauge are too extreme. Work is needed to improve the program to shorten the delay. This will be investigated in the future and it may not be possible.  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 system has been constructed that can add water, vibrate the concrete and increase the pressure. Tuning the air pressure has been completed. Future work will be to streamline the automated SAM.  A new tool to help clean the top rim of the SAM has also been produced. It shows a lot of promise to help reduce the time needed for the test. This is being sent for production so that the states can provide comments.   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   In this research study, the authors have been determining the critical degree of saturation for different mixtures. In addition for some of these mixtures they will be measuring the formation factor and correlating it with the sorptivity coefficient. Consequently, they will work on finding a correlation between the second sorptivity coefficient value and the critical degree of saturation. As described in section 4, the apparent formation factor has been calculated on concrete samples with 25 different mixture designs and samples are being preconditioned in order to test their sorptivity coefficient.   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 begun. Concrete is being tested at room temperature, elevated temperature, and also in cold temperatures. This will provide important information to FHWA about when the air void system returns in the concrete.  **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. 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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 and hold biweekly meetings. |

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| **Significant Results:** |
| **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:** |