A Brief Look at the Effects of Adding Water and/or Lack of Curing of Residential / Commercial Concrete

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INTRODUCTION and BACKGROUND

The primary focus of the Going beyond ACI 332: Commercial / Residential Enhanced Durability Concrete study is the resistance to degradation of concrete in the presence of commercial magnesium chloride deicing salts. However, the Tennessee Concrete Association (TCA) Executive Director inquired if Tennessee Technological University (TTU) researchers could show a general loss of durability (not just due to magnesium chloride deicing salt) resulting from water added at the jobsite and/or the lack of proper curing. This brief paper is an effort to comply.

There are a wide variety of concrete durability concerns. However, this brief look will focus on only three of these: freeze-thaw resistance, corrosion of reinforcement, and cracking. Freeze-thaw resistance decreases with increasing absorption and decreasing tensile strength. ACI 332-14 specifies a 28-day compressive strength of 4000-psi in the presence of deicing salts as well as an air content range based on coarse aggregate size and limitations on supplementary cementing materials replacement percentages to ensure adequate freeze-thaw resistance. Corrosion of reinforcement becomes more likely as chloride permeability increases (surface resistivity of concrete decreases). ACI 332-14 specifies a 28-day compressive strength of 4000-psi in the presence of deicing salts to minimize corrosion of reinforcement. ACI 332-14 does not specify a maximum water-to-cementing-materials (w/cm) ratio for freeze-thaw or corrosion protection. However, the commentary accompanying the code recommends a w/cm ratio less than 0.45.

Concrete with more water (a higher w/cm) typically experiences more shrinkage than lower water content concrete mixtures. In addition, concrete with lower static modulus of elasticity is likely to deform more due to load-associated or thermal stresses. Concrete with a lower tensile strength is more likely to crack due to stresses resulting from shrinkage, load-associated stress, or thermal stresses.

MATERIALS

The same materials were used for Phase 1 and Phase 2 of the project.

PROCEDURE

The control mixtures used in Phase 2 of the study are from Phase 1 of this TCA study (Tennessee Concrete Winter 2019/20). Table 1 shows characteristics of the control mixtures. Table 2 shows water-cementing materials ratios from the control and variable mixtures used in Phase 2.

Table 1. Characteristics of Control Mixtures for Phase 2 of the TCA Study

Control Mixture	Total Cementing Materials (pcy)	Water-cementing materials ratio	Supplementary Cementing materials (percent of total cementing materials)	Chemical Admixtures
3500-psi Commercial.	480	0.521	22 Class C Fly Ash	Air + MRWR
ACI 332 Commercial	564	0.443	20 Class C Fly Ash	Air + MRWR
CRED 1 36F/4MK	520	0.390	36 Class F Fly Ash + 4 Metakaolin	Air + MRWR + HRWR

Table 2. Water-Cementing Materials Ratios for Control and Variable Mixtures

Mixture	Control	+2 gal/CY	No Cure	Both
3500-psi Commercial	0.521	0.555 (+6)	0.521	0.555 (+6)
ACI 332 Commercial	0.443	0.473 (+7)	0.443	0.473 (+7)
CRED 1 36F/4MK	0.390	0.422 (+8)	0.390	0.422 (+8)
< ACI 332-14 commentary recommended maximum?			Yes	No

Unfortunately, only one batch of each mixture / variable was produced due to limited space in the 125º F drying oven. Nine batches were produced for Phase 2. Twelve 4x8-inch cylinders and 9 3x6-inch cylinders were fabricated from each batch. Four 4x8-inch cylinders and 3 3x6-inch cylinders (for absorption after boiling) were tested at 28-days to produce the results shown in Table 3. The remainder of the cylinders will be used to measure the effect of commercial deicing salt containing magnesium chloride on concrete properties.

RESULTS

Table 3 shows 28-day properties for the three control mixtures (from Phase 1) and the three variables applied to each control mixture used in Phase 2. None of the mixtures (control or variable) had been subjected to deicing salts prior to testing. Testing procedures were the same as those used in Phase 1 of the study (Tennessee Concrete Winter 2019/20).

Table 3. Effect of Adding Water and/or No Curing on 28-day Concrete Properties

Mixture	Control	+2 gal/CY	No Cure	Both
Surface Resistivity in kilohm-cm (% change from control)				
3500-psi Commercial.	12.3	11.2 (-9)	8.3 (-33)	7.1 (-42)
ACI 332 Commercial	12.4	11.5 (-7)	10.5 (-15)	8.3 (-33)
CRED 1 36F/4MK	30.3	33.6 (+11)	25.8 (-15)	22.8 (-25)
Chloride Permeability Category		Low	Moderate	High
Compressive Strength in psi (% change from control)				
3500-psi Commercial.	5200	3860 (-26)	2980 (-43)	2790 (-46)
ACI 332 Commercial.	6610	5370 (-19)	4060 (-39)	3890 (-41)
CRED 1 36F/4MK	8770	7110 (-19)	5980 (-32)	5610 (-36)
Meets Comp. Strength Specification / Expectation?			Yes	No
Split Tensile Strength in psi (% change from control)				
3500-psi Commercial.	440	350 (-21)	295 (-33)	260 (-41)
ACI 332 Commercial.	530	550 (+4)	375 (-29)	350 (-34)
CRED 1 36F/4MK	565	605 (+7)	495 (-12)	455 (-20)
Static Modulus of Elasticity in million psi (% change from control)				
3500-psi Commercial.	3.95	4.10 (+4)	3.65 (-8)	3.45 (-13)
ACI 332 Commercial	4.30	4.20 (-2)	3.95 (-8)	3.95 (-8)
CRED 1 36F/4MK	4.65	4.60 (-1)	4.90 (+5)	4.85 (+4)
Absorption after Boiling (% change from control)				
3500-psi Commercial	5.28	5.66 (+7)	4.99 (-6)	6.11 (+16)
ACI 332 Commercial	4.96	5.07 (+2)	5.11 (+3)	5.51 (+11)
CRED 1 36F/4MK	4.28	3.95 (-8)	4.05 (-5)	4.72 (+10)
High Performance Concrete Level Absorption (<5%)?			Yes	No

ANALYSIS

General

Table 3 also includes some analysis such as percent gain or loss compared to properties of the control mixture. The surface resistivity section of Table 3 also shows the chloride permeability category at 28-days. The compressive strength section of Table 3 shows whether the mixture / variable met specifications / expectations for 28-day compressive strength. The expected compressive strengths for the three mixtures are 3500, 4000, and 4500-psi, respectively. The absorption after boiling section of Table 3 shows whether the mixture / variable was able to achieve high performance concrete (HPC) level absorption (< 5%) at 28-days.

Damage

Statistical analysis are not possible with only one batch per mixture / variable. Therefore, the damage level assumptions in Table 4 will be used to characterize the change in 28-day properties. An unfavorable change in properties will be considered an increase in absorption or a decrease in surface resistivity, strength and/or modulus.

Table 4. Damage level Assumptions and Definitions

Damage Level	Description	Effect on 28-day Property
0	None or Insignificant	<5% unfavorable change in property
1	Significant	≥5 to <10% unfavorable change in property
2	Minor	≥10 to <20% unfavorable change in property
3	Severe	≥20 to <40% unfavorable change in property
4	Catastrophic	≥40% unfavorable change in property

Damage Level by Mixture

Table 5 shows relative damage by mixture. The 3500-psi commercial mixture had the highest mean damage level (2.33) and the highest number of catastrophic level damages (4). The higher level of damage is probably due to the several factors: highest w/cm of any mixture tested, lowest cementing materials content of any mixture tested, and least desirable properties of the control mixture. The ACI 332 commercial mixture fared much better with a lower mean damage level (1.67) and lower number of catastrophic level damages (1). The CRED 1 mixture fared the best with the lowest mean damage level (1.33) and lowest number of catastrophic level damages (0). Water addition and lack of curing had a greater effect on the higher w/cm mixtures and a lesser effect on the lower w/cm mixtures.

Table 5. Damage Level by Mixture

Mixture	Level 0	Level 1	Level 2	Level 3	Level 4	Mean Damage Level
3500-psi Commercial	2	3	2	4	4	2.33
ACI 332 Commercial	4	3	3	4	1	1.67
CRED 1 36F/4MK	7	0	4	4	0	1.33

Damage Level by Phase 2 Variable

Table 6 shows relative damage by Phase 2 variable. Addition of water generated the lowest mean damage level (0.93) and the lowest number of severe damage levels (2) and the lowest number of catastrophic damage levels (0). That is not to say that addition of water did not cause damage to 28-day properties. Addition of water significantly damaged properties related to concrete durability in 8 of 15 cases. Lack of curing generated much greater change than the addition of +2-Gallon/CY. Lack of curing had a higher mean damage level (1.80) and generated a higher number of severe damage levels (5) and catastrophic damage levels (1). Lack of curing significantly damaged properties related to concrete durability in 11 of 15 cases. As expected the combination of water addition and lack of curing produced the maximum damage to 28-day concrete properties. The combination of variables had the highest mean damage level (2.67) and generated the highest number of severe damage levels (5) and catastrophic damage levels (4).

The combination of variables significantly damaged properties related to concrete durability in 14 of 15 cases.

Table 6. Damage Level by Phase 2 Variable

Mixture	Level 0	Level 1	Level 2	Level 3	Level 4	Mean Damage Level
+ 2 Gallons/CY	7	4	2	2	0	0.93
No cure	4	2	3	5	1	1.80
Both	1	1	4	5	4	2.67

Damage Level by Engineering Property

Table 7 shows relative damage by measured 28-day property. Compressive strength suffered the greatest mean damage (3.11) and the highest number of severe damage levels (4) and catastrophic damage levels (3) combined. Compressive strength suffered significant damage in all cases. Split tensile strength and surface resistivity were second and third in damage, respectively. Split tensile strength suffered the second greatest mean damage (2.33) and the second highest number of severe damage levels (5) and catastrophic damage levels (1) combined. Split tensile strength suffered significant damage in 7 of 9 cases. Surface resistivity suffered the third greatest mean damage (2.11) and the third highest number of severe damage levels (3) and catastrophic damage levels (1) combined. Surface resistivity suffered significant damage in 8 of 9 cases. Static modulus of elasticity and absorption after boiling suffered relatively little mean damage, 0.56 and 0.47, respectively. Neither static modulus of elasticity or absorption after boiling suffered a single severe or catastrophic damage. That is not to say neither suffered any damage. Both of these properties suffered significant damage in 4 of 9 cases.

Table 7. Damage Level by 28-day measured Property

	Level 0	Level 1	Level 2	Level 3	Level 4	Mean Damage Level
Surface Resistivity	1	2	2	3	1	2.11
Compressive Strength	0	0	2	4	3	3.11
Split Tensile Strength	2	0	1	5	1	2.33
Static Modulus of Elasticity	5	3	1	0	0	0.56
Absorption after Boiling	5	1	3	0	0	0.47

Freezing and Thawing Potential

Table 8 shows properties and parameters related to the potential for freeze-thaw damage. The potential for freeze-thaw damage greatly increased in the 3500-psi commercial mixture due a decrease in tensile strength and an increase in absorption after boiling resulting from Phase 2 variables. In addition, the Phase 2 variables forced the 3500-psi commercial mixture to never meet the ACI 332 specification for compressive strength or the ACI 332 commentary recommendation for w/cm ratio.

The CRED 1 mixture is a totally different story. The potential for freeze-thaw damage only slightly increased in the CRED 1 mixture due to a decrease in tensile strength or an increase in absorption after boiling resulting from Phase 2 variables. The addition of two gallons of water per cubic yard seemed to have no harmful effect on absorption after boiling or split tensile strength. In addition, the Phase 2 variables did not stop the CRED 1 mixture from maintaining HPC level absorption or meeting the ACI 332 specification for compressive strength and the ACI 332 commentary recommendation for w/cm ratio. The CRED 1 mixture appeared to have the strongest resistance to Phase 2 variables. A fail-safe or invulnerable concrete mixture is not possible but CRED 1 withstood the damage far better than the other mixtures.

The potential for freeze-thaw damage increased substantially in the ACI 332 commercial mixture due to a decrease in tensile strength and an increase in absorption after boiling resulting from Phase 2 variables. The addition of two gallons of water per cubic yard seemed to have only a small harmful effect on absorption after boiling or split tensile strength. The lack of curing greatly reduced the split tensile strength and increased the absorption after boiling of the ACI 332 commercial mixture. The lack of curing variables also caused the compressive strength to either fail ACI 332 specifications of come uncomfortably close to failing. ACI 332 commercial mixture performance was intermediate between the other two mixtures.

Table 8. Freeze-Thaw Damage Potential

Mixture / Variable	Absorption after Boiling in Percent	Split Tensile Strength in psi	Meets ACI Code Compressive Strength (≥4000-psi)?	Meets ACI Commentary w/cm (<0.45)?
3500-psi Commercial Control	5.28	440	Yes 5200	No 0.521
3500-psi Commercial + 2 Gallons/CY	5.66	350	No 3860	No 0.555
3500-psi Commercial No Cure	4.99	295	No 2980	No 0.521
3500-psi Commercial Both	6.11	260	No 2790	No 0.555
ACI 332 Commercial Control	4.96	530	Yes 6610	Yes 0.443
ACI 332 Commercial + 2 Gallons/CY	5.07	550	Yes 5370	No 0.473
ACI 332 Commercial No Cure	5.11	375	Yes 4060	Yes 0.443
ACI 332 Commercial Both	5.51	350	No 3890	No 0.473
CRED 1 36F/4MK Control	4.28	565	Yes 8770	Yes 0.390
CRED 1 36F/4MK + 2 Gallons/CY	3.95	605	Yes 7110	Yes 0.422
CRED 1 36F/4MK No Cure	4.05	495	Yes 5980	Yes 0.390

CRED 1 36F/4MK Both	4.72	455	Yes 5610	Yes 0.422

Reinforcement Corrosion Potential

Table 9 shows properties and parameters related to the potential for reinforcement corrosion damage. The chloride permeability category is probably the most important factor for reinforcement corrosion damage. In 8 of 9 cases, the Phase 2 variables caused an increase in the permeability category. This increase in permeability category increases the likelihood of reinforcement corrosion, especially in cases where the permeability is in the high category. All Phase 2 variables caused the chloride permeability of the 3500-psi and ACI 332 commercial mixtures to be categorized as high. A high chloride permeability category greatly reduces the expected service life of the concrete. Again, the CRED 1 mixture suffered some damage but fared far better than the other mixtures.

Table 9. Reinforcement Corrosion Damage Potential

Mixture / Variable	Chloride Permeability Category	Meets ACI Code Compressive Strength (≥4000-psi)?	Meets ACI Commentary w/cm (<0.45)?
3500-psi Commercial Control	Moderate	Yes 5200	No 0.521
3500-psi Commercial + 2 Gallons/CY	High	No 3860	No 0.555
3500-psi Commercial No Cure	High	No 2980	No 0.521
3500-psi Commercial Both	High	No 2790	No 0.555
ACI 332 Commercial Control	Moderate	Yes 6610	Yes 0.443
ACI 332 Commercial + 2 Gallons/CY	High	Yes 5370	No 0.473
ACI 332 Commercial No Cure	High	Yes 4060	Yes 0.443
ACI 332 Commercial Both	High	No 3890	No 0.473
CRED 1 36F/4MK Control	Low	Yes 8770	Yes 0.390
CRED 1 36F/4MK + 2 Gallons/CY	Low	Yes 7110	Yes 0.422
CRED 1 36F/4MK No Cure	Moderate	Yes 5980	Yes 0.390
CRED 1 36F/4MK Both	Moderate	Yes 5610	Yes 0.422

Cracking Potential

Table 9 shows properties and parameters related to the potential for cracking. A higher w/cm ratio increases the amount of drying shrinkage expected in concrete. The stresses generated from drying shrinkage must be resisted by tensile strength in concrete elements not free to move. Most residential and commercial concrete elements are restrained by the base, subgrade or other concrete elements. The combination of an increase in shrinkage potential and a decrease in tensile strength makes cracking far more likely.

Load-associated and thermal changes can cause stresses and deformations in concrete elements. The magnitude of these stresses and deformations is dependent on the modulus of elasticity among other factors. Lower modulus of elasticity leads to larger deformations and possibly cracking. However, the decreases in modulus of elasticity due to Phase 2 variables were relatively small and therefore did not seem as great a problem as shrinkage.

The 3500-psi commercial mixture fared the worst and the CRED 1 fared the best. As expected, the ACI 332 commercial mixture was intermediate in performance.

Table 10. Cracking Damage Potential

Mixture / Variable	Static Modulus of Elasticity in million psi	Split Tensile Strength in psi	Meets ACI Commentary w/cm (<0.45)?
3500-psi Commercial Control	3.95	440	No 0.521
3500-psi Commercial + 2 Gallons/CY	4.10	350	No 0.555
3500-psi Commercial No Cure	3.65	295	No 0.521
3500-psi Commercial Both	3.45	260	No 0.555
ACI 332 Commercial Control	4.30	530	Yes 0.443
ACI 332 Commercial + 2 Gallons/CY	4.20	550	No 0.473
ACI 332 Commercial No Cure	3.95	375	Yes 0.443
ACI 332 Commercial Both	3.95	350	No 0.473
CRED 1 36F/4MK Control	4.65	565	Yes 0.390
CRED 1 36F/4MK + 2 Gallons/CY	4.60	605	Yes 0.422
CRED 1 36F/4MK No Cure	4.90	495	Yes 0.390
CRED 1 36F/4MK Both	4.85	455	Yes 0.422

OBSERVATIONS

Conclusions seem inappropriate for a study with only one batch of each mixture / variable. Therefore, the authors have decided to offer some observations and recommend that these observations be verified with further research and literature examination. The following observations are based on the limited data available in this brief look.

1. A commercial mixture with a w/cm ratio above the ACI 332-14 commentary recommended (<0.45) is likely to suffer severe to catastrophic damage to 28-day compressive and tensile strength as well as chloride permeability when subjected to water addition or lack of curing. The probable damage experienced by the mixture greatly increases the likelihood of freeze-thaw, reinforcement corrosion, and cracking durability problems.
2. A TTU commercial and residential enhanced durability (CRED) mixture with a w/cm ratio well below the ACI 332-14 commentary recommended (<0.45) is likely to suffer

minor to severe damage to 28-day compressive and tensile strength as well as chloride permeability when subjected to water addition or lack of curing. The probable damage is not only less than that of a high w/cm mixture but the damaged properties are still in excess of ACI 332-14 specification and commentary requirements / recommendations. Therefore, the probable damage experienced by the mixture only slightly to moderately increases the likelihood of freeze-thaw, reinforcement corrosion, and cracking durability problems.

3. As expected, an intermediate w/cm mixture was much more likely to have durability problems than the CRED mixture and less likely than the high w/cm ratio commercial mixture when subjected to addition of water or lack of curing. An intermediate w/cm commercial mixture just meeting the ACI 332-14 commentary recommended (<0.45) is likely to suffer severe damage to 28-day compressive and tensile strength as well as chloride permeability when subjected to water addition or lack of curing.
4. The addition of 2-gallons/CY of water typically results in much lower damage to 28-day properties and consequently the probability of durability problems than lack of curing. As expected, the combination of both variables produces devastating damage (always severe or catastrophic) to 28-day compressive and tensile strengths as well as chloride permeability. Therefore, the combination of both variables makes durability problems much more likely.
5. Static modulus of elasticity and absorption after boiling suffered relatively little damage compared to compressive strength, tensile strength and chloride permeability due to the addition of water or lack of curing. Neither static modulus of elasticity or absorption after boiling suffered a single severe or catastrophic damage due to either variable or the combination of variables. That is not to say neither suffered any damage. Both of these properties suffered significant damage in 4 of 9 cases.

WHAT'S NEXT?

The variable mixtures began cycling between 7 days of drying at 125º F and 7-days of soaking in a 15% (by weight) solution of commercially-available deicing salt containing magnesium chloride in July of 2020. Testing of properties (strength, modulus, and absorption) is planned for January and March of 2021. Results and analysis of these tests should be available in the summer of 2021.

ACKNOWLEDGEMENTS

The authors appreciate the financial and technical support provided by the Tennessee Concrete Association.

The authors would like to thank Denny Lind of BASF for extensive donations of chemical admixtures to the project. Also, the authors would like to thank Martin Medley for donations of materials used in this project.

In addition, the authors would like to thank Mark Davis for his patience and skill in fabrication, maintenance, and repair of the equipment.

Further, we appreciate the financial support of the TTU Department of Civil and Environmental Engineering.

Finally, the authors appreciate the administrative, financial and information technology support provided by the TTU Center for Energy Systems Research, particularly Dr. Satish Mahajan, Robert Craven, Etter Staggs, and Anysa Milum.

REFERENCES

Detailed references are shown in Tennessee Concrete Winter 2019/20.

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