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Effect Of Deicing Chemicals And Fly Ash On Durability And Mechanical Properties Of Concrete

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EFFECT OF DEICING CHEMICALS AND FLY ASH ON DURABILITY AND MECHANICAL PROPERTIES OF CONCRETE

By

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Degree: Master of Science in Civil Engineering

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Joseph Useldinger-Hoefs

May 2023

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ABSTRACT

Deicing chemicals, such as Sodium Chloride (NaCl), lowers the freezing point of water, resulting in less skidding, less hydroplaning, and more friction on roadways. NaCl has limitations regarding its deicing capabilities; therefore, a supplement should be used to decrease corrosion and aid in lowering the freezing point of water. Incorporating AMP in NaCl brine aids in bonding to the road's surface and further lowers the water's freezing point. This study was conducted to explore the optimum solution of AMP and Sodium Nitrite ($NaNO_2$) and the impact 20% fly ash has on durability. Hardened properties were used to compare the impact of AMP. Durability was determined following ASTM C-666 and BNQ-2621. Results indicated minimal losses in hardened properties or scaling resistance with up to 15% AMP. The freeze-and-thaw results indicated a decrease in resistance in the durability factor when the cement was replaced with fly ash according to ASTM C-666.

Chapter 1 INTRODUCTION

1.1 General

Northern cities and towns need roadways resistant to ice and snow since vehicles are more prone to skidding in these environments due to lowered friction. Deicing products, including Sodium Chloride (NaCl), Magnesium Chloride (MgCl), Calcium Chloride ($CaCl_2$), and acetate mixtures, are among the many available options. NaCl is the most used deicer in the U.S. as of 2005; 57% of those surveyed report that NaCl is their first choice for roadway deicing (WTIC 2005). The estimated cost of using NaCl is $7 per lane mile, calcium chloride costs $42 per lane mile, magnesium chloride costs $36 per lane mile, and acetate mixtures can cost up to $135 per lane mile; therefore, the market for NaCl is robust since it is less expensive and readily available (MNDOT 2014*)*. Deicers decrease waters freezing point, allowing ice to melt in colder temperatures. NaCl can lower the freezing point to -6 °F in laboratory settings, while the conservative estimate in the field is approximately 15°F. Decreasing harm to the environment, providing corrosion defense, and softening ice and snow are among the benefits of using additives to NaCl, such as AMP, and Sodium Nitrite ($NaNO_2$). AMP is a commercial product made of magnesium chloride and other chlorides to aid in bonding NaCl to the surface of the road. The City of Grand Forks currently uses a 15% AMP solution. The City of Grand Forks currently does not use $NaNO_2$; however, it could be used to decrease corrosion in reinforcement if the hardened properties and durability of concrete can be sustained and if there is not a dramatic price increase. Proper deicer use is of the utmost importance to maintain road conditions, keep costs low, and reduce skidding resulting in keeping citizens safer.

1.2 Problem Statement

Deicing salt solutions can contribute to concrete's ability to resist freeze-thaw and salt scaling. Deicing agents can detrimentally affect concrete properties due to scaling, freeze-thaw resistance, spalling, cracking, and reinforcement bar corrosion, in addition to vegetation withering and underground water pollution (Wang et al. 2006, Sisomphon et al. 2010, Sutter et al. 2008, Shi et al. 2009, Shi et al. 2010). Salt scaling resistance generally decreases with an increase in fly ash content, which could be partially related to lower strength with shorter curing periods of 3–28 days (Bouzoubaa and Fournier 2005, Bouzoubaa et al. 2008, Sun et al. 2002). The tests that determine the durability and scaling resistance are based on their respective ASTM or BNQ standard. Each test has questions about their representation of the real world. For example, the ASTM C672 standard was withdrawn in 2021 due to fly ash's lack of durability and is not representative of fly ash performance in the field. The other tests have similar problems; however, are more representative than ASTM C672. Concrete beams in a freeze-thaw environment scale more readily in a salt solution than in water. The increase in scaling will result in higher mass loss, with twice as much mass loss than concrete tested in pure water, according to tests performed following ASTM C672 (Hanjari et al. 2011). This project determines the effects of deicing solutions on 100% Portland cement (control) and partial fly ash replacement using pure NaCl solution, 5% AMP replacement, 10% AMP replacement, 15% AMP replacement, 20% AMP replacement, and a NaNO2 solution. The scaling resistance, relative dynamic modulus of elasticity (RDME), mass loss comparison, compressive strength, flexural strength, and tensile strength, will be compared using the different variables. For the City of Grand Forks, the project will utilize aggregate from companies such as Strata, Kost, and Aggregate Industries. Concrete will be utilized to evaluate the aggregates supplied by each company, in addition to the effect these deicers have on each aggregate. A recommended deicer solution will be provided based on the results of testing several aggregate types and deicing solutions.

1.3 Project Objectives:

- Establishing the ideal ratios of sodium nitrite (NaNO2), AMP, and NaCl brine solution to ensure the durability of concrete in terms of freeze-thaw, scaling resistance, hardened characteristics, and safety.
- Using the association between scaling and the percentage/spacing of air voids in fresh concrete to assess the effects of these ideal deicing chemical ratios on air voids in hardened concrete.
- Determine the impact fly ash replacement for Portland Cement has on durability following ASTM C666 using relative dynamic modulus of elasticity and mass loss percentages.
- Evaluate the impact of $NaNO_2$ on compressive strength and durability of concrete.

- Make a recommendation based on the data for the optimum solution for a deicing solution.

1.4 Thesis Organization

The project is explained in Chapter 1, coupled with which deicers are currently in use and their intended use. The justification for incorporating NaNO2 into a deicing solution in addition to the suggested additions. The goals of the project and what we expect to gain from the project are also introduced in Chapter 1.

The literature review gets underway in the second chapter. An in-depth examination of the standards employed and the collection of research on freeze-thaw durability from scaling, the effect fly ash has on the strength and durability of concrete and the currently employed methods and justifications for them, in addition to the evidence of deicers' effects on concrete are reviewed.

Chapter 3 will describe the methodology. The decisions made to make each mix of concrete, how the deicers were decided, and the standards followed are described.

Chapter 4 will illustrate the results of the project.

Chapter 5 will be a discussion, conclusion, recommendations, and potential future works.

Chapter 2 LITERATURE REVIEW:

2.1 Deicers

2.1.1 NaCl

NaCl dissolved in water, or brine is preferable to using solid NaCl as a deicer. Brine pre-wets the surface, rapidly lowering water's freezing point, and is not easily removed by elements such as wind and water, unlike solids. The eutectic point, or the lowest temperature at which water will freeze, is -6°F with an optimal brine-to-water ratio of 23.3% dissolved NaCl by weight and 76.7% water (Kadi and Janajreh, 2019). Drebushchak et al. (2017) challenged that the eutectic point of water decreases to -16.6°F by using Differential Scanning Calorimetry. An endothermic reaction converts to an exothermic reaction at -16.6°F for a 23.3% dissolved NaCl solution.

2.1.2 AMP

AMP acts as a binding agent to concrete surfaces, allowing equipment to remove slush and resulting in safer driving conditions. AMP is a propriety corrosion inhibitor solution of calcium chloride and magnesium chloride. AMP has been proven to lower the freezing point of NaCl further than just the 23.3% NaCl brine. AMP used as a supplement to NaCl can accelerate ice melting and reduce salt runoff due to its sticking properties. The adhesiveness of AMP results in a decrease in NaCl runoff from environmental events such as wind, vehicle traffic, and water runoff. There has been little research done on the durability or hardened properties of concrete when exposed to this propriety solution.

2.1.3 $NaNO_2$

Another solute can be added to NaCl and AMP to reduce corrosion in reinforcement structures. Sodium Nitrite ($NaNO_2$) inhibits corrosion in carbon steel bars when dissolved in a 0.7-0.9 Molar ratio of $NaNO_2$ to NaCl (Hayyan 2012). The effect of $NaNO_2$ has been studied using galvanostatic, potentiodynamic polarization curves, and linear polarization to determine the impact on steel corrosion. The tests showed that the presence of NO_2 ions has produced a beneficial effect on concrete when provided with the proper amount of NO_2 ions (Wedding et al. 1986). Wood (1970) studied the impact of $NaNO_2$ on compressive strength and found it is the most effective chemical to inhibit steel corrosion; however, its use decreased the concrete's 28-day compressive strength. Another study found similar results in terms of compression strength as well and found that the higher amount of NO_2 ions further inhibited corrosion (Das and Pradhan 2022). From the impact on hardened properties, there is some evidence showing the impact on durability as well. Introducing $NaNO_2$ decreases the concrete's air void pore sizes (Li et al. 2016). Decreasing pore size can reduce durability in terms of freeze-thaw resistance and cause high mass loss while decreasing concrete strength. AMP and $NaNO_2$ have not been studied together; therefore, the impact of AMP and $NaNO_2$ on concrete strength and durability was determined.

2.2 Freeze-Thaw Durability

There is concrete evidence of the impact deicing salts have on the durability of concrete. The frost action of ice increases the volume of water by 9%; therefore, expansion from a liquid to a solid can expand in pores resulting in cracking in the capillary (Fagerlund 1977).

Osmotic forces act when there are not enough pores to accommodate the expansion of water; therefore, freezing introduces pressure on the remaining liquid water migrating to unfrozen pores. Concrete with proper air void percentages and spacing is critical in allowing water to enter the needed pores at the proper spacing. As surface ice melts, it is followed by the melting of pore ice, causing a contraction in volume. This results in the absorption of external liquid by thawing concrete (Geiker and Thaulow 1996), or it is a mixture of micro ice growth and suction during thawing (Jacobsen et al. 1999). Increasing the degree of saturation consequently leads to internal damage or scaling on the surface of the concrete. Some newer research indicates the deterioration is due to a multitude of factors including crystallization pressure, low-temperature suction, and ice expansion pressure(Liu et al. 2014, Mesbah et al. 2011, Wang et al. 2021). The freezing rate introduces a new variable when deicing salts are introduced especially in the expansion of water in capillaries (Kropp & International Union of Testing and Research Laboratories for Materials and Structures 1995). The European Union performed a study in 1995 using expansion measurement, microscopical analysis (SEM, confocal microscope, etc.), mercury intrusion (MIP), and acoustic emission techniques to determine the impact deicing salts have on concrete roads. Other researchers have further researched deicers' impact on concrete durability. Deicers can impact concrete durability in terms of limitation of air voids, crystallization, increase in saturation, exposure to thermal shock, and volume expansion, and may exacerbate osmotic pressures (Li et al. 2016, Richardson n.d.; Xie et al. 2017). The introduction of deicing chemicals is not expected to dramatically differentiate from the lab to the field; however, the introduction of deicers can impact air void spacing and begin to lower the durability of concrete in freezing and thawing cycles.

2.2.1 Proper Air Content

Litvan (1975) argued that the best defense against scaling is optimizing the percentage of air voids. Properly cured concrete with proper air entrainment prevents mass loss from freeze and thaw cycles. Concrete containing quality aggregate and well-designed proportions with 6±1% entrained air is more resistant to freeze-thaw cycles and scaling (Öttl, 2006). Richardson agreed with Öttl; however, Richardson proposed the optimum amount of air voids is dependent on aggregate size. Proposing proper air entraining percentages ranging from 4.5% to 7.5% depending on maximum aggregate size (Richardson, n.d.).

Air content just like air void spacing has a key impact on the impact of concrete when in weathering conditions. To withstand the impacts of freezing and thawing, concrete that is subjected to cold temperatures and deicing agents requires air entrainment. Additionally, air content increases concrete's plasticity and reduces bleeding. For concrete to be durable, there should be a minimum and maximum air content limit because every 1% increase in air content reduces concrete's compressive strength by 5% to 6%. For the same amount of air-entraining admixtures, concrete with more fine cement has less air content. For a given amount of air-entraining admixture, air content decreases as cement fineness increases. Additionally, the air content is reduced when fly ash is added, so a larger amount of air-entraining admixture is required to meet the design criteria. When designing the mix it is important to note that the implementation of fly ash should decrease due to using the same amount of admixture throughout the mixes (Kosmatka and Wilson, 2016).

2.2.2 Air Void Spacing and Distrubution

The spacing factor is crucial to determine the impact of scaling and freeze-and-thaw. The critical spacing factor required to avoid salt scaling is between 200-300 μm (0.00787 – 0.0118 in.) (Valenza and Scherer 2007). The spacing is critical in concrete to dissipate hydraulic pressure. Air bubble-to-bubble lengths need to be short enough that both osmotic and hydraulic pressure can be eliminated or minimized. Many small air voids have been recommended to reduce spacing. A higher critical spacing factor increases the likelihood of physical deterioration when undergoing freeze and thaw cycles and using deicing chemicals (Pigeon and Pleau 1995). As noted with $NaNO_2$, deicing chemicals have been shown to impact the durability of concrete. Overall, deicers can disturb a concrete's ability to resist freeze-thaw not only from chemical processes but also disarrange air void spacing in concrete. The importance of a lower spacing factor is critical when exposing the concrete to deicers due to the already negative impact of chlorides; therefore, it is important to design the proper spacing to aid in resistance to freeze-thaw to help offset some negatives when using deicing chemicals.

Air content and air void spacing are both important, but not the only thing that needs to be considered. Jiu proposed that the fractal dimension air void size distribution had a greater impact on resistance to freeze and thaw than air void spacing. Providing a regression equation to compare fractal dimension to freeze-thaw resistance. Jin et al. (2013) found freeze-thaw durability factor increased with the increasing fractal dimension of air void size distribution. Noting air void spacing is critical; however, the fractal dimensions are important to note when designing concrete that is resistant to freeze-thaw. A hardened air void analyzer following ASTM C457 can help determine fractal dimensions in hardened concrete which can be used to design future concrete mixes. Figures 1 a and b depict two concrete samples. Figure a has frost damage after placement and b is a sample without frost damage. In comparison to the specimen without frost damage, the specimen with frost damage has huge pores created by the creation of ice lenses and numerous internally damaged structures (Yi et al. 2011).

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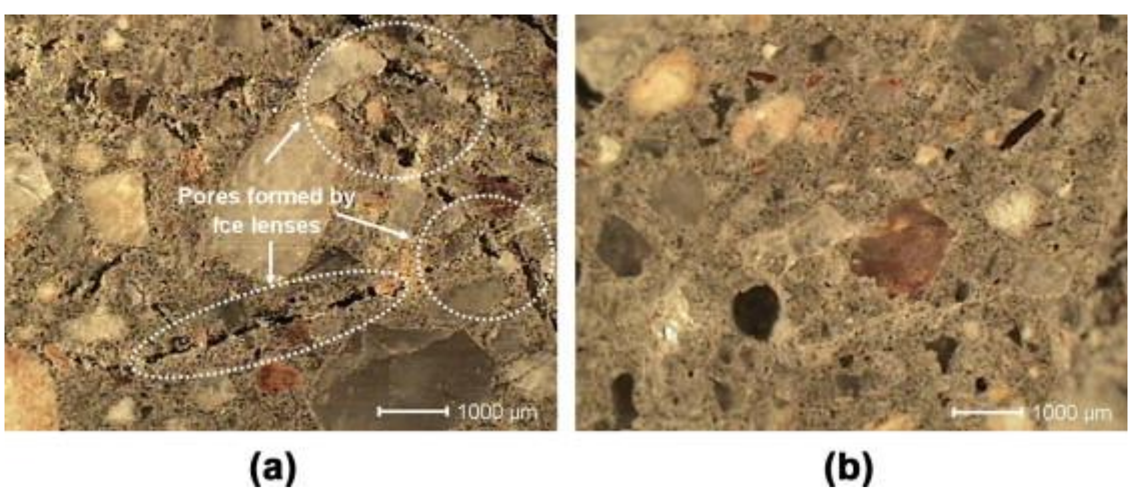


Figure 1. Comparison of Frost Damage vs No Frost Damage. (a). Sample after 28 days Subjected to damage from Freeze Thaw and (b) No Frost Damage (Yi et al., 2011).

2.3 Factors to Limit Scaling and Freeze-Thaw

Concrete with poor resistance to freezing and thawing will scale, potentially expand, and crack. Factors to consider when designing concrete that resists freeze-and-thaw are water-to-cement ratio (w/c), porosity, air content, air void spacing, and aggregate type. W/C has been proven to have a large impact on the durability of concrete. Concrete with a poor w/c ratio is known to have low workability and concrete with a high w/c ratio tends to have lower strengths compared to concretes with a 0.40 w/c. The impact the w/c ratio has on durability is similar; whereas, concrete with a low or too high w/c ratio can have a detrimental impact on concrete's durability. Kim et al. found that the increase in the w/c ratio increased the porosity, chloride diffusion coefficient, and sorptivity while a lower w/c ratio decreased mechanical properties (Kim et al. 2014). A lower w/c ratio has been studied to be a hindrance as well. According to Neville (1995), shrinkage stresses at lower w/c cause cement paste to crack and/or lose its binding to the aggregate, resulting in a reduction in strength. Concrete with a lower permeability or low w/c ratio have shown to increase resistance to freeze and thaw; however, a balance needs to be met to not allow shrinkage or cement cracking.

2.4 Fly Ash

Mineral admixtures, such as fly ash, are often used to replace 5–50% of cement. These mixtures can significantly enhance various properties, such as long-term compressive strength, modulus of elasticity, permeability, and durability due to filling voids and pozzolanic reactions (Chidiac and Panesar 2008, Nili and Zaheri 2011). Adding fly ash decreases the concrete's compressive strength in the early curing stages based on the percentage of cement replaced by fly ash (Dandautiya & Singh, 2019). Implementation of fly ash has been proven to enhance the durability of concrete compared to Portland cement. Nath and Starker (2011) tested fly ash's ability to resist chloride implementation, absorptivity, and shrinkage. The shrinkage of concrete containing fly ash resulted in similar shrinkage after 21 days compared to 100% Portland cement; however, the rate of shrinkage decreased with concrete containing fly ash after 28 days. The implementation of fly ash has shown a significant reduction of capillary suction due to the inclusion of fly ash, resulting in a decrease in absorptivity for up to 180 days. When fly ash is exposed to rapid chloride penetration, the tests have shown up to a 65-70% decrease in Cl^- permeability after 180 days compared to a control. Introducing fly ash creates a challenge with scaling resistance and freeze-thaw durability. The lack of resistance is more likely to occur when the concrete is exposed to low temperatures relatively early before the pozzolanic reaction can develop. Allowing sufficient time for concrete containing fly ash to develop strength is highly recommended before subjecting it to scaling practices due to the time the pozzolanic reaction takes to convert into CSH and develop a strong paste matrix (Naik et al., 2005). There has been some contradictory evidence on the durability of fly ash using lab tests. ASTM C672 has shown that concrete containing fly ash is not representative of fly ash in the field; therefore, ASTM C672 has been withdrawn in 2021. The Canadian scaling standard, BNQ 2621, has been used as a substitute. BNQ has shown better representative results; however, it still does not represent the performance in the field (Distlehorst 2015). This can be due to the time required to cure for concrete containing fly ash and allowing the pozzolanic reaction to fully develop before exposing it to freezing temperatures. The scaling tests are consistent, so the test is valuable to compare the difference in deicing agents; however, the tests do not exactly represent concrete in the field. ASTM C-666 has shown better results compared to the respective scaling standards; however, the same problems can exist where they are not exactly representative of field samples.

2.5 Hardened Properties after Freezing and Thawing

Zhang et al. (2021) studied mechanical properties after freezing and thawing, establishing that the concrete's mechanical properties, such as resistance to freeze-and-thaw, resistance to expansion, and cracking, will perform better if the pore size distributions are smaller due to air bubbles at smaller air void distances. Air bubbles in properly distributed concrete will aid in resistance to scaling and cracking in freeze-and-thaw environments as previously mentioned. Yamane et al. (1978) have shown that concrete curing in lower temperatures has shown to increase compressive strength; however, it is important to note that settling times may last longer in colder temperatures due to the lack of evaporation and the hydration process. There needs to be time for concrete to cure before concrete can be exposed to freezing and thawing conditions. ASTM C-666 requires 14 days of curing in 100% relative humidity (RH); therefore, the proper curing period is critical to retaining the mechanical properties of concrete. Figure 2 illustrates that the compressive strength decreases with the increasing freeze-thaw cycles under different static load conditions. The same study shows similar results with dynamic compressive strength, flexural strength, splitting tensile strength, and relative dynamic modulus of elasticity (Zhang et al. 2021). The impact freeze-thaw has is evident; therefore, the resistance to freeze and thaw needs to be considered due to the loss in mechanical properties. Air voids, air spacing, w/c ratio, saturation, and aggregate size among several other factors have an impact on concrete's ability to resist freeze and thaw.

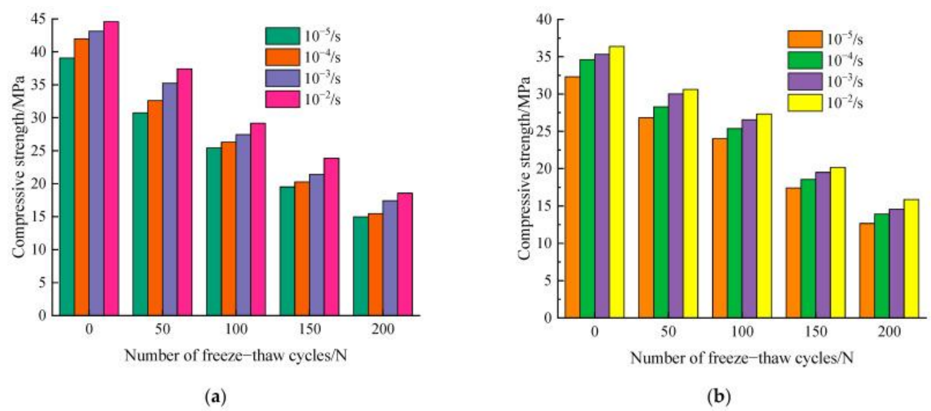


Figure 2. Compressive Strength after Freeze Thaw Cycles: (a). w/c=0.45, (b) w/c=0.55 (Zhang et al. 2021).

2.6 Salt Scaling

Salt scaling is superficial damage caused by a saline solution freezing to the surface of a concrete body, removing ''small flakes or chips'' in the paste (Valenza and Scherer 2007).

Salt scaling is aesthetically displeasing due to coarse aggregate exposure and increases the scaled specimen surface's sensitivity to the penetration of fluids and detrimental ions such as chloride. One of the main concerns when constructing outside in colder climates is that sidewalks, driveways, and bridge decks are influenced by salt scaling. Chlorides and water have easier access to the aggregates, leading to quicker deterioration because the coarse aggregate becomes exposed. Concrete that contains 4.5-7.5% air can aid in preventing scaling issues (Öttl 2006, Richardson, n.d.). One must render it obvious that salt scaling is not equivalent to conventional freeze/thaw damage, which is brought on by internal crystallization and is distinguished by a decrease in stiffness and strength. Salt scaling does not necessarily impact the mechanical properties of concrete but makes concrete more susceptible to ingress of moisture and chloride penetration. Deicing agents should not necessarily impact the hardened properties of concrete directly; however, if the paste starts to scale, ingress can start to break down the strength of the concrete after freezing and thawing conditions which can impact hardened properties.

2.7 Modulus of Elasticity and Poisson's Ratio

Within the elastic range of a material, the modulus of elasticity (MOE) is the ratio of applied stress to the corresponding strain. A material's MOE is a measurement of how much deformation it can withstand when subjected to an external load. The MOE of concrete is a crucial component since it affects how the structure responds to loads. Concrete with a normal weight has a MOE of 2 million to 6 million pounds per square inch. Similar to how concrete's compressive strength in psi can be roughly calculated as 57000 times the square root of MOE's flexural strength (Kosmatka and Wilson 2016).

The usual range of Poisson's ratio for concrete, according to Kosmatka and Wilson (2016), lies between 0.15 and 0.25. However, this range may change depending on the type of aggregate, the mix design, the age of the concrete, and other factors. The standard range for Poisson's ratio of Portland Cement concrete is 0.20 to 0.21. For concrete containing fly ash, there is a slight adjustment from 0.15-0.25 to 0.16-0.21. In general, the higher the Poisson's ratio the lower the strength of concrete (Nguyen et al. 2016).

Chapter 3 METHODOLOGY

3.1 Experimental Plan

Figure 3. Outline for Project

The first step we made in designing concrete is determining aggregate properties. The specific gravities and absorptions of coarse and fine aggregates are used to determine the volume of the concrete batch. According to research, coarse aggregate specific gravity is a key determinant of concrete density and weight and may be used to assess the material's strength and quality (Salem and Pandey 2015). The fineness modulus of the fine aggregate determines the proportion of sand in a concrete mix. Both are important in determining the volume of a concrete batch and determining strengths and the amount of sand in a mixture. When developing a mix, the specific gravities, fineness modulus, nominal maximum aggregate sizes, and absorptions are all factored into account. They are also discovered when completing a gradation following AASHTO T85 and other AASHTO or ASTM specifications. The design for the appropriate slump is based on the nominal maximum aggregate size. While the absorptions aid in the designer's optimum w/c ratio design. To effectively develop a concrete mix, each is crucial.

The mixes from Aggregate Industries were designed based on the recommendations provided by the company. Strata mixes were designed based on mixes currently in use by the company. Kost did not have any recommendations; therefore, the concrete mix was designed considering aggregate properties, w/c ratio, nominal maximum aggregate size, and batch volumes. Moisture corrections were determined by the mix’s given absorptions and current moisture conditions. Figure 4 is a screenshot of the mix provided to the researchers from Strata Corporation and was used closely for the mix for the project.

SINCE 1910

Hand Placed Pavement, Curb & Gutter, Walks, and Drives

Suggested Mix Design

Material	Weight *lbs./CY*	Specific Gravity	Abs. Vol. *CF/CY*	Trial Batch *CY*
Cement	451	3.15	2.295	**451**
Pozzolan # 2	0.0	2.20	0.000	**0**
Fly Ash	113	2.50	0.723	**113**
Coarse Agg #1	1640.0	2.69	9.770	**1640**
Coarse Agg # 2 NDDOT Cl43 P-Rock	125.0	2.69	0.745	**125**
Coarse Agg. #3	0.0	2.70	0.000	**0**
Fine Agg.	1380.0	2.68	8.252	**1380**
Add Water	237.4	1.00	3.805	**28.5**
Free Water	0.0	1.00	0.000	incl in Aggs
Air Content		6.0%	1.639	
Totals =	3946		27.2	

Total Cementitious = 564.0 Lbs.
% Fly Ash = 20%
% Pozzolan = 0%
w/c = 0.42
Fines to total Agg. Ratio by wt = 0.421
Fine Agg free Moisture = 0.0%
Coarse Agg free Moisture = 0.0%
Coarse Agg #2 free Moisture = 0.0%
Total Free Moisture (lbs.) = 0
Calculated Unit Weight = **144.93** lbs./CF
Target 28 Day Strength = 4000 psi

Total Agg = 3145.0 lbs/CY
Rock = **52%**
P Rock = **4%**
Sand = **44%**

Air Free Unit Weight = 154.2 lbs/CF
Paste Volume = 8.46 CF
C/V = 0.554

Estimated Admixture Dosages

	oz./cwt	oz./CY	ml./batch
AE 90 (AEA) =	1	5.6	0.0
AE 400 (AEA) =	0	0	0.0
Polyheed 1020 (WR) =	2	11	0.0
Glenium 7500 (HRWR) =	0	0	0.0
MasterSet AC534 (Accel) =	0	0	0.0
Delvo (retarder) =	0	0	0.0

Mortar Fraction = 16.72 CF
% Air of Mortar Fraction = 10%
% Air of Paste Volume = 19%

Figure 4. Strata Corporation Mix Design (Strata, 2021.).

3.2 Aggregate Testing

Table 1 depicts the bulk specific gravity, saturated surface dry specific gravity (SSD), and absorption of aggregates from Aggregate Industries, Strata Corporation, and Kost Industries depicted from the lab. The results provided by Aggregate Industries matched what was established in the lab, following AASHTO T-84. The results were similar for Strata, with a little tweak the researchers determined from the aggregate properties rather than what Strata reported. Both absorption and fineness modulus were used to determine the amount of coarse and fine aggregate in the concrete mix to find the volume of the mixes for the design. Figures 5 and 6 show the information on coarse and fine aggregate from Strata that was given to the researchers. The coarse aggregate data table acquired from Strata is shown in Figure 5, and the fine aggregate attributes are shown in Figure 6. Bulk-specific gravity and SSD conditions were similar; however, a little different. The mix design followed the aggregate properties in the lab rather than directly from the company due to slight potential differences in each batch of aggregate. The laboratory replicated the aggregate qualities of Aggregate Industries.

Table 1. Aggregate Properties Found in Lab

Properties	Aggregate Industries		Strata		Kost	
	Coarse Aggregate Properties	**Fine Aggregate Properties**	**Coarse Aggregate Properties**	**Fine Aggregate Properties**	**Coarse Aggregate Properties**	**Fine Aggregate Properties**
Bulk	2.69	2.66	2.605	2.668	2.64	2.64
SSD	2.72	2.67	2.634	2.678	2.688	2.65
Absorption	0.86	0.56	0.91	0.36	0.86	0.38
Fineness Modulus	Not Applicable	2.5	Not Applicable	2.86	Not Applicable	2.74

TESTS OF COARSE AGGREGATE QUALITY

Terracon

Report Number:	M1211001.0018
Service Date:	04/12/21
Report Date:	05/14/21 Revision 2 - Correct Intermediate Aggregate
Task:	Pit 225 - Northern Sand and Gravel

860 9th St. NE, Unit K
West Fargo, ND 58078
701-282-9633

Client

Strata Corporation
Attn: Hank Hauge
PO Box 39
West Fargo, ND 58078-0039

Project

Plant Tests 2021 - Strata Corporation
210 12th Ave. NW
West Fargo, ND 58078

Project Number: M1211001

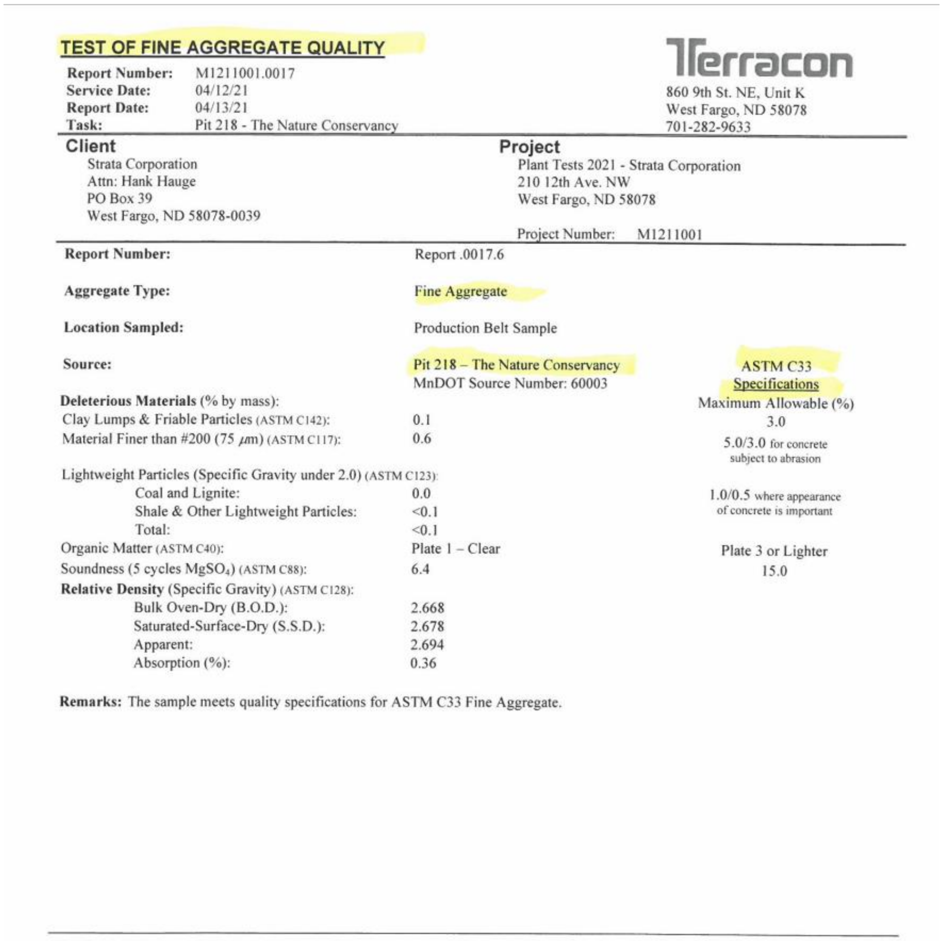
Report Number:	Report .0018.4	
Aggregate Size:	NDDOT Size 3 & 4, 1"-#4	
Location Sampled:	Production Belt Sample	NDDOT Specifications <u>Section 802</u>
Source:	Pit 225 – Northern Sand & Gravel MnDOT Source Number: 60006	
		Maximum Percent by Weight of the Plus No. 4 Fraction
Deleterious Materials (% by mass):		
a. Lightweight Particles (AASHTO T 113 NDDOT Modified)	0.4	0.7
b. Hard Iron Oxide Particles (NDDOT Modified)	0.1	4.0/2.0 [a]
c. Lignite and Other Coal (AASHTO T 113 NDDOT Modified)	0.0	0.5
d. Soft Particles Exclusive of a, b & c (NDDOT Modified) (includes clay, soft iron oxide and other friable materials)	<0.1	2.5
e. Thin (4:1) or Elongated (3:1) Pieces (ASTM D4791 NDDOT Modified)	0.2	15.0
Thin	0.2	
Elongated	0.0	
f. Material Passing #200 Sieve (AASHTO T 11)	<0.1	1.0
g. L.A. Abrasion (AASHTO T 96) (Grading B)	25	40.0
h. Soundness 5 cycles $MgSO_4$ (AASHTO T 104) [b]	3.9	12.0
Fractured Faces: (%1 Face + #4)(ASTM D5821)	36.2	
Carbonates: (%) (MnDOT Method lab manual 1209)	29.7	
Relative Density (Specific Gravity)**:** (AASHTO T 85)		
Bulk Oven-Dry (B.O.D.):	2.666	
Saturated-Surface-Dry (S.S.D.):	2.690	
Apparent:	2.732	
Absorption (%):	0.91	

Remarks: The sample meets quality specifications for NDDOT 802 Coarse Aggregate.

a). *Spall repairs and bridge deck overlays. the maximum iron oxide particles shall be 2.0 percent.*

b). *The test was performed using $MgSO_4$ soak solution, which typically yields higher soundness losses than the specified $NaSO_4$ soak solution.*

Figure 5. Strata Coarse Aggregate Properties (Strata, 2021).



TEST OF FINE AGGREGATE QUALITY

Terracon
860 9th St. NE, Unit K
West Fargo, ND 58078
701-282-9633

Report Number:	M1211001.0017
Service Date:	04/12/21
Report Date:	04/13/21
Task:	Pit 218 - The Nature Conservancy

Client
Strata Corporation
Attn: Hank Hauge
PO Box 39
West Fargo, ND 58078-0039

Project
Plant Tests 2021 - Strata Corporation
210 12th Ave. NW
West Fargo, ND 58078

Project Number: M1211001

Report Number:	Report .0017.6	
Aggregate Type:	Fine Aggregate	
Location Sampled:	Production Belt Sample	
Source:	Pit 218 – The Nature Conservancy MnDOT Source Number: 60003	ASTM C33 Specifications
Deleterious Materials (% by mass):		Maximum Allowable (%)
Clay Lumps & Friable Particles (ASTM C142):	0.1	3.0
Material Finer than #200 (75 μm) (ASTM C117):	0.6	5.0/3.0 for concrete subject to abrasion
Lightweight Particles (Specific Gravity under 2.0) (ASTM C123):		
Coal and Lignite:	0.0	1.0/0.5 where appearance of concrete is important
Shale & Other Lightweight Particles:	<0.1	
Total:	<0.1	
Organic Matter (ASTM C40):	Plate 1 – Clear	Plate 3 or Lighter
Soundness (5 cycles $MgSO_4$) (ASTM C88):	6.4	15.0
Relative Density (Specific Gravity) (ASTM C128):		
Bulk Oven-Dry (B.O.D.):	2.668	
Saturated-Surface-Dry (S.S.D.):	2.678	
Apparent:	2.694	
Absorption (%):	0.36	

Remarks: The sample meets quality specifications for ASTM C33 Fine Aggregate.

Figure 6. Strata Fine Aggregate Properties (Strata, 2021).

3.3 Concrete Mix Design and Proportions

Table 2 presents the mix design provided by Aggregate Industries for a compressive strength of 4,000 psi. The mix was modified to include 20% fly ash since the provided mix was proportioned for 15% fly ash replacement. The expected slump values were designed to meet 3-4 inches and the expected air content was 5-8%. The water to cement plus pozzolan (W/(C+P)) ratio was 0.43. The project compared the control to the fly ash replacement to establish the impact fly ash has on the hardened properties and durability of concrete. A moisture correction accounted for the drying of the materials to create uniform aggregate properties and to ensure that the mixes and proportions were similar since repeatability was essential for the project.

Table 2 also presents the concrete proportions for the Strata mix. Strata provided a design mix with 20% fly ash that is used in the city of Grand Forks. The team decided that the water reducer was not necessary after testing with the values given by Strata in the lab. The fresh properties were consistent with the recommendations without the plasticizer. The team calculated the equivalent cement mix and compared the results to 20% fly ash. The mix was designed for a compressive strength of 4,000-4500 psi after 28 days. The expected fresh properties were a 3–5-inch slump and a 5-8% air content. The 20% fly ash mix design was used to determine the impact of different deicing solutions on concrete.

Table 2 presents the concrete proportions for the Kost mix as well. Kost did not provide a mix design nor aggregate properties; therefore, the team designed an entire mix from scratch using aggregate properties, w/c ratio, moisture corrections, and more. The mix was designed to follow the 4000-4500 psi compressive strength after 28 days. 20% fly ash was subsumed for Portland cement to attempt to recreate similar concrete to the proportions from other companies. After trial mixes, it was found that no plasticizer was needed to be within the 3-5” slump and to aid in workability when casting. Air content was designed for a 4.5-7.5% air content.

Table 2. Concrete Mix Proportions

Type of Material	**Plasticizer**	**Aggregate Industries**		**Strata**		**Kost**	
		Control	**20% Fly Ash**	**Control**	**20% Fly Ash**	**Control**	**20% Fly Ash**
		Weight (lbs/CY)	**Weight (lbs/CY)**	**Weight (lbs/CY)**	**Weight (lbs/CY)**	**Weight (lbs/CY)**	**Weight (lbs/CY)**
Cement		564	450	564	451	619.2	516
Fly Ash		0	113	0	113	0	103.2
Coarse Aggregate #1		1767	1753	1651	1640	1861	1855
Coarse Aggregate #2 (P-Rock)		N/A	N/A	118	125	N/A	N/A
Fine Aggregate		1338	1328	1398	1380	1202	1194
Water		242	242	237.4	237.4	260	260
Air Entrainment (mL/ft^3)	Eucon AEA-92	2.47	2.47	6.16	6.16	3.04	3.04

Water Reducer (mL/ft^3)	Eucon WR-91	18.53	18.53	0	0	0	0
w/(C+P)		0.43	0.43	0.42	0.42	0.42	0.42

3.4 Curing

Curing follows AASHTO R-39 for hardened properties. The concrete will be kept in a moist curing room for 7, 28, and 56 days for the control mix and 20% fly ash mix, respectively. For concrete that has been exposed to deicing salts, a bath in the appropriate deicer will be used, just like lime baths are used for concrete made with fly ash. The effect of the deicer on mechanical characteristics was examined after curing in the bath. The deicer will be applied to the concrete after BNQ 2621-900, which is a separate curing process from the one used for hardened properties.

3.5 Fresh Properties and Mixing

The fresh properties that were determined included slump, air content, unit weight, and Super Air Meter (SAM) number.

3.5.1 Workability

Workability is the ease with which freshly mixed concrete may be placed and finished. Good workability without segregation is required for concrete. Using the slump test to gauge consistency is one of the accepted methods of gauging workability. The slump cone test follows AASHTO T-119.

Implementation of fly ash has been shown to decrease water demand mostly due to fineness and surface area. The decrease in water demand should increase the slump if every variable stayed constant.

3.5.2 Air Content

The air content of concrete is normally found using the pressure method following AASHTO T-152. Air content of concrete is critical for resistance to freeze-thaw and colder environments. Mass loss due to freeze and thaw cycles is prevented by properly cured concrete with enough air entrainment. Scaling and freeze-thaw cycles are less likely to affect concrete with high-quality aggregate and proportions that are well-designed (Ottl 2006). Depending on the maximum aggregate size, recommended appropriate air entraining percentages are between 4.5% and 7.5% (Richardson n.d.).

Implementation of fly ash will tend to decrease the fresh air content of concrete due to the surface area and fineness of fly ash compared to Portland Cement.

3.5.3 SAM Number

A SAM meter was used to determine the spacing of air in fresh concrete. A SAM number of 0.20 is adequate for providing durable concrete regardless of the limit provided by field testing; however, further research has provided an in-depth investigation of the correlation between the SAM number and air spacing in concrete. Figure 7 clearly shows that the decrease in SAM number resulted in lower spacing and vice versa. The same study showed that a lower SAM number resulted in a higher air percentage and a higher SAM number resulted in a lower air content (Hall et al. 2020). 0.2 micrometers are a guideline following ACI- 201.2R. The SAM meter can provide an outcome that is consistent with the hardened concrete features that can establish a factor of freeze-thaw durability, and testing may be completed in 7–12 minutes. A hardened air void analysis could be done to follow up on data received from the lab and correlate the SAM number the researchers received and the hardened air void analysis following ASTM C457. Fresh properties followed their respective ASTM or AASHTO standard. Fresh properties were determined in every mix and reported in the results.

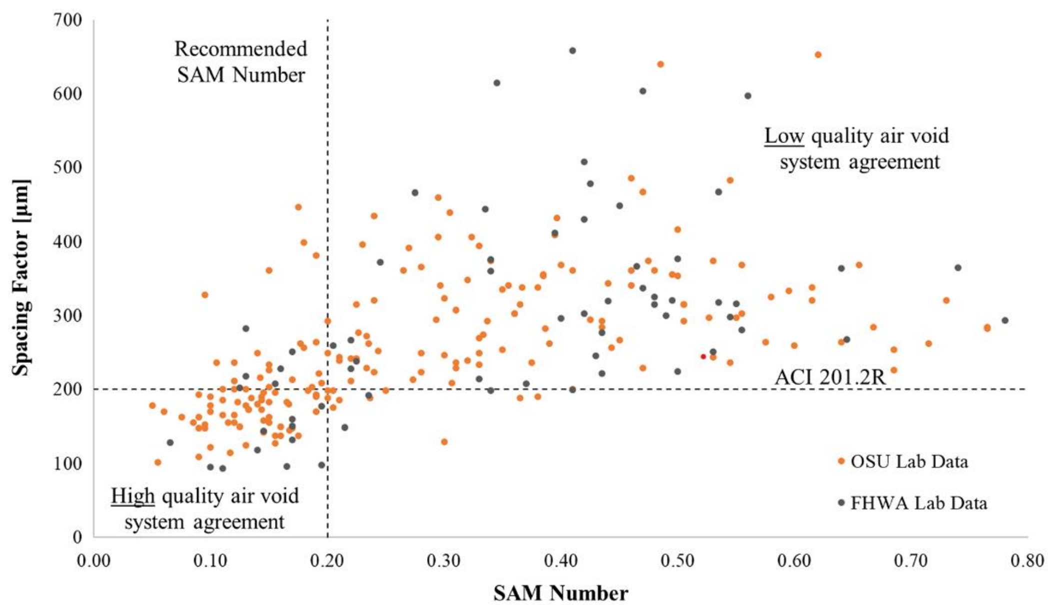


Figure 7. Correlation Between SAM and Spacing (Hall et al., 2020).

3.5.4 Unit Weight

The unit weight of concrete is the mass of a unit volume of concrete. It is typically measured in kilograms per cubic meter or pounds per square foot, and another name for it is the density of concrete. The unit weight of concrete is affected by the mix ratios, aggregate density, air content, and other variables. The unit weight of concrete is important to know because of its relationship with structural design in modulus of elasticity, and the general stability of concrete.

The implementation of fly ash is expected to decrease the weight of concrete; however, is not supposed to decrease the long-term strength of concrete nor the durability of the concrete (Kosmatka and Wilson 2016).

3.5.5 Mixing and Standards

The tests follow the respective standard from AASHTO (Table 3). For uniformity, sampling and mixing were essential, thus they were done in a rigorous accordance with AASHTO R-39 and R-60. Each batch was 3.75 cubic feet in size; therefore, it needed to comply with the standards to ensure the concrete was fresh for as long as possible throughout casting and testing. As previously mentioned, the fresh properties will be tested after each batch of concrete is made. The SAM number was tested following the instructions given by Oklahoma State researchers and producers. The air content and the SAM number were both obtained using the SAM meter. Cylinders and beams were cast following respective standards, de-molded after 24 hours of settling, and then sent to their respective curing locations following AASHTO R39. Cylinders and flexural beams were made for hardened property testing following AASHTO R-39.

Table 3. AASHTO and ASTM Standards for Fresh, Hardened, and Durability Properties

Test	Company	Standard
Concrete Mixing	ASTM/AASHTO	C-192 (8.1.2)/R 39
Concrete Sampling	ASTM/AASHTO	C172/ R60
Slump	ASTM/AASHTO	C143/ T-119
Air Content	ASTM/AASHTO	C231/ T-152
Unit Weight	ASTM/AASHTO	C138/ T-121
Cylinders	ASTM/AASHTO	C192 (8.1-8.5)/ R-39
Curing For Beams	ASTM/AASHTO	C192 (9.4)/ R-39 (8.4)
Compression Test for Cylinders	ASTM/AASHTO	C39/ T-22
Tensile Test for Cylinders	ASTM/AASHTO	C496/ T-198
Flexural Beam Test	ASTM/AASHTO	C78/ T97
Freeze-Thaw Resistance	ASTM/AASHTO	C666/ T-161, T-188
Scaling Resistance	ASTM/BNQ	C672 (withdrawn) / 2621-900

3.6 Hardened Properties

Concrete samples, including cylinders, flexural beams, and freeze-and-thaw beams, were cast and cured following AASHTO-R-39 standards. Three compressive cylinders were cast, two for tensile, two for modulus of elasticity, and one flexural beam per day tested.

The hardened properties, such as compressive, flexural, modulus of elasticity, and tensile strength, were tested after 7, 28, and 56 days, respectively. Seven cylinders were tested per day needed and one flexural beam; therefore, 21 cylinders and 3 flexural beams were made per batch for hardened properties. The average of the samples was the number representing each strength included in this paper. The coefficient of variation (COV) was used for compressive strength; however, COV was only used when there was a sample size greater than three. COV was not calculated for tensile, MOE, or flexural due to the lack of sample size.

3.6.1 Compression Tests

Three cylinders were made to be broken at 7, 28, and 56 days of curing. The compressive strength follows procedure AASHTO T-22. Compressive strength is the ability of concrete to withstand latitudinal loads or axial loads. Portland Cement achieves approximately 90% of strength at 28 days and is mostly dependent on the aggregate type, w/c ratio, and environmental conditions.

It is anticipated that fly ash will relatively weaken the compressive strength after 7 days. The pozzolanic reaction of Silicon Dioxide and Aluminum Oxide takes longer than Sodium Oxide in Portland Cement to hydrate, which contributes to the decrease in strength. According to Dandautiya and Singh (2019), fly ash concrete often catches Portland Cements' compressive strength at 28 days or later.

3.6.2 Flexural Strength

The Flexural Strength of Concrete was determined following AASHTO T97. Beam specimens of size 6inch * 6inch * 21inch were cast according to the standard AASHTO T23. The flexural strength is a critical value to determine at what strength does the concrete become brittle in bending and will shear with no warning. The maximum load at failure was found and flexural strength was calculated. One beam per respective day was tested and presented in the data set.

3.6.3 Tensile, Modulus of Elasticity, and Poisson's Ratio

The Splitting Tensile Strength of Concrete was determined following AASHTO T 198 standard. Concrete performs poorly in tension, so it is critical to add steel reinforcement to compensate for some tensile strength. Deicing salts can cause steel bars to corrode; as a result, adding $NaNO_2$ to a deicing solution can aid reinforced concrete to help it sustain longer. Two tensile tests will be tested on each respective day, and the average will be presented in the data set.

In a material's elastic range, the modulus of elasticity (MOE) is the ratio of applied stress to the corresponding strain. A material's MOE is a gauge of how much deformation it can sustain under external loads. There will be two samples used to obtain the MOE and Poisson's ratio for each day tested and the average will be used in the results. The concrete made could be stiffer due to the increased modulus of elasticity. The shortening of concrete components under compressive stress, as well as owing to creep and shrinkage, is directly related to the elastic modulus. Internal stresses in reinforced concrete structures are distributed differently amongst columns, beams, and walls as a result of concrete shortening (Alsalman et al., 2017). The tests follow ASTM C469.

The lateral to longitudinal strain ratio is known as Poisson's ratio. It may be used to find strains when there is a temperature shift and is used to calculate shear modulus. The expected Poisson’s ratio can range from 0.15-0.25; however, the widely accepted value for Poisson’s value is 0.20 (Kosmotka and Wilson 2016).

3.7 Durability Tests

3.7.1 Freeze-and-Thaw

Freeze-and-thaw testing followed the respective AASHTO or ASTM standards (Table 3). The mass loss and relative dynamic modulus were determined every 36 cycles and continued until the concrete reached 288 cycles in the freeze-and-thaw environment. Each sample spent a total of 59 days—or 8 weeks and 3 days—in the freeze-thaw apparatus. Two samples were tested, and the average values were included. According to ASTM C-666, the freeze-thaw experiment was used to determine how 20% fly ash replacement affected RDME and mass loss differently from 100% Portland cement. The results established the impact of fly ash on concrete durability.

Two freeze-thaw beams were made per batch, two for the control and two for the fly ash batch. The freeze-and-thaw beams were placed in the freeze-and-thaw environment for testing after 14 days of curing in the moist curing room. The project team tested the samples of every 36 freeze-and-thaw cycles and determined the mass, length, and dynamic modulus of elasticity. The beams were subjected to final testing, and the results were reported after 288 cycles.

3.7.2 Scaling

Six scaling samples were prepared for each company representing each respective deicer being tested (NaCl, 5% AMP,10% AMP, 15% AMP, 20% AMP, and NaNO2). Scaling samples followed the Canadian standard BNQ-2621 since the ASTM standard was withdrawn in 2021. Scaling was assigned a score of 1-5 based on BNQ-2621 test standards. BNQ-2621 requires subjecting the scaling concrete samples to moist curing for 14 days, air curing for 14 days, then pre-saturation in the solution for 7 days before exposure to the freeze-and-thaw environment to determine scaling resistance. Figure 8 is a visual interpretation of the differences between the ASTM standard and the BNQ standard from Montreal. The team will replace the chemical solution with the chemical being tested and will use 5,10-,15-,25-, and 56-day testing for visual and mass.

	ASTM C672	NQ 2621-900
Saline solution	4% $CaCl_2$ (or 3% NaCl)	3% NaCl
Specimens	• Prism measuring 280 × 230 × 75 mm • Surface area of a prism: 460 cm^2 • After the concrete has stopped bleeding, the surface is brushed with a medium-stiff brush	• Prism measuring 280 × 230 × 75 mm • Fresh concrete cast in a bottom-draining mold
Curing of specimens	• 14 days at 100% RH • 14 days at 50% RH	• 14 days at 100% RH • 14 days at 50% RH • 7 days of presaturation with saline solution
Freeze–thaw cycles	• 50 cycles of 24 h • Freezing: –18 °C in concrete in 16–18 h • Thawing: 23 °C for 6–8 h	• 56 cycles of 24 h • Freezing: 16 ± 1 h of which a maximum of 7 h and a minimum of 12 h at –18 °C concrete temperature • Thawing: 8 ± 1 h at 23 °C
Evaluation of surface quality	After 5, 10, 15, 25, and 50 cycles • Visual assessment of surface aspect 0: no scaling 5: severe scaling	• After 7, 21, 35, and 56 cycles • Visual assessment of surface aspect 0: no scaling 5: severe scaling • Measure of cumulative mass of scaled-off particles in kg/m^2
Acceptance criteria	The standard does not specify acceptance criterion. However, some organizations specify a maximum mass of scaled-off particles after 50 cycles. This limit is generally between 0.8 and 1 kg/m^2.	After 56 cycles, the cumulative mass of scaled-off particles must be lower than 0.5 kg/m^2

Figure 8. Comparison of ASTM and BNQ Scaling Standards (Houehanou et al., 2010)

CHAPTER 4 RESULTS

4.1 Fresh Properties Results

Table 4 provides the results for fresh properties, following the proportions listed in Table 2 for their respective company. The AEA-92 and WR-91 plasticizers can have differences in mixing up to 2-3 mL. The difference in fresh properties is due to the slight differences in the water reducer added. Studies indicate that fly ash has a low-water demand compared to Portland cement, which should result in a higher slump; therefore, the increase in slump from the control to 20% fly ash can be deduced as a difference in admixture or mixing angle for Aggregate Industries. Due to its enhanced fineness and carbon content, fly ash requires less water than Portland cement. The uniformity was more intriguing when fly ash was added and the air content continuously decreased. Fly ash can significantly affect fresh qualities because of its fineness, spherical form, chemical composition, and other characteristics(Raghav et al. 2021). The incorporation of a water reducer can have a slight impact on the air content of concrete depending on the water reducer (Plante et al. 1989). Table 2 provided the amount of water reducer implemented for the Strata mix; however, table 4 showed there was minimal impact on air content from a water reducer. The researchers recommend using a hardened air void analyzer to supplement the SAM number and establish the SAM meter's accuracy. Implementing a hardened air void analyzer will provide a higher degree of confidence in the air void distribution.

Table 4. Fresh Properties

			Deicers					
Measurement	**Control**	**20% Fly Ash**	**NaCl**	**5% AMP**	**10% AMP**	**15% AMP**	**20% AMP**	**0.7M $NaNO_2$**
(a) Aggregate Industries								
Slump (inches)	4.75	3.0	3	2.5	2.75	3	2.75	3
Air Content (%)	8	6.3	6.5	5.5	6	6	4.6	5.8
SAM (psi)	0.07	0.26	0.30	0.28	0.29	0.30	0.31	0.28

Unit Weight (lb/ft^3)	142.1	141	140.5	144.4	148	148.4	140.9	143.3
(b) Strata								
Slump (inches)	3.75	3.75	3	3.8	3	3.5	3.5	3.7
Air Content (%)	7.1	5.6	5.1	5.4	5.1	5.9	5.5	6.0
SAM (psi)	0.21	0.29	0.30	0.21	0.24	0.22	0.33	0.35
Unit Weight(lb/ft^3)	140.8	143	145	142.5	145.2	141.9	144	146
(c) Kost								
Slump (inches)	3.5	4.75	3.5	4	4.5	3.5	4.5	4
Air Content (%)	6.4	5.3	4.2	4.8	5.5	4.8	5.5	5.2
SAM (psi)	0.21	0.30	0.28	0.29	0.26	0.32	0.26	0.21
Unit Weight(lb/ft^3)	144.1	144	141	144.6	143.4	144.1	143.4	144.2

4.2 Hardened Properties of the Concrete

4.2.1 Aggregate Industries

Figure 9 illustrates the compressive strength of the Aggregate Industries mix. The control resulted in the highest compressive strength; however, introducing fly ash lowered the compression strength at 7 days due to the amount of time needed to cure since the pozzolanic reaction takes more than seven days to reach the Portland cement compression strength. The compression strength increased by 100 psi when AMP addition was increased from 0% to 20%; however, the difference in curing in different deicing agents did not alter the results drastically as mentioned in the literature review. The error bars included represent the variation between samples.

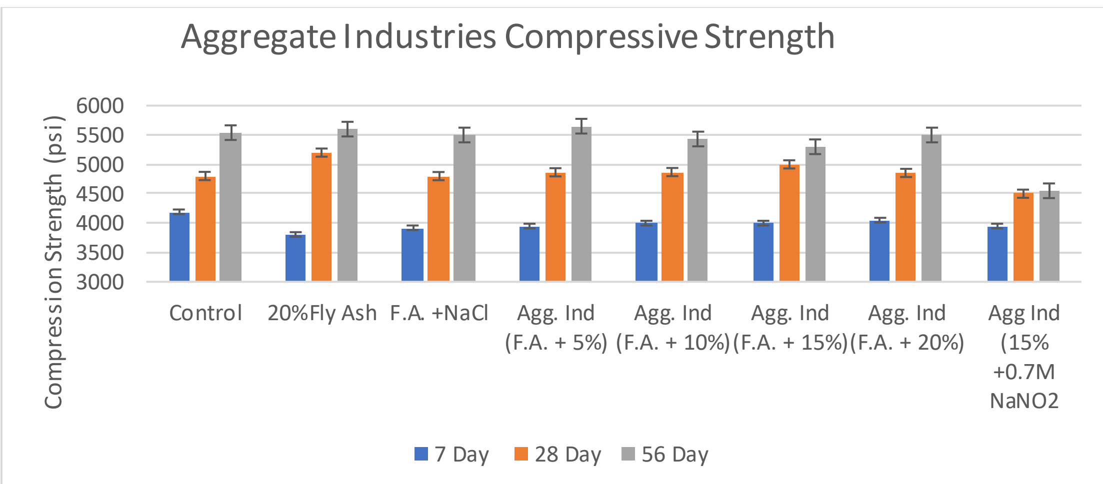


Figure 9. Compressive strength of the Aggregate Industries Mix.

Figure 10 shows similar results with the tensile strength as the compression strength. There did not seem to be a considerable difference in strengths when exposed to different deicing agents when there was no freeze-thaw. The only difference was some inconsistency in the 56-day strengths; however, tensile strength was consistently between 370-450 psi for the 28-day tensile strengths.

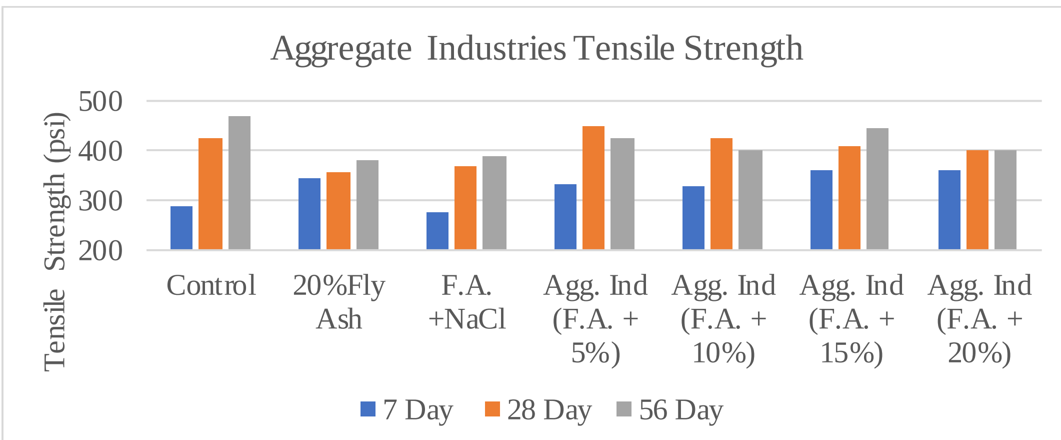


Figure 10. Tensile Strength of the Aggregate Industries Mix

Figure 11 illustrates the flexural strength of the Aggregate Industries mix. The general rule for flexural strength is at least 650psi for 28 days or about 10-12% of the compressive strength of concrete. The flexural strengths obtained far exceeded minimum requirements and at times reached 20% of the compressive strength. Increasing AMP or implementing NaCl did not impact the tensile or flexural strength by more than 70 psi for 56 days; therefore, the results indicate that increasing AMP does not impact flexural or tensile strength by a measurable amount for Aggregate Industries.

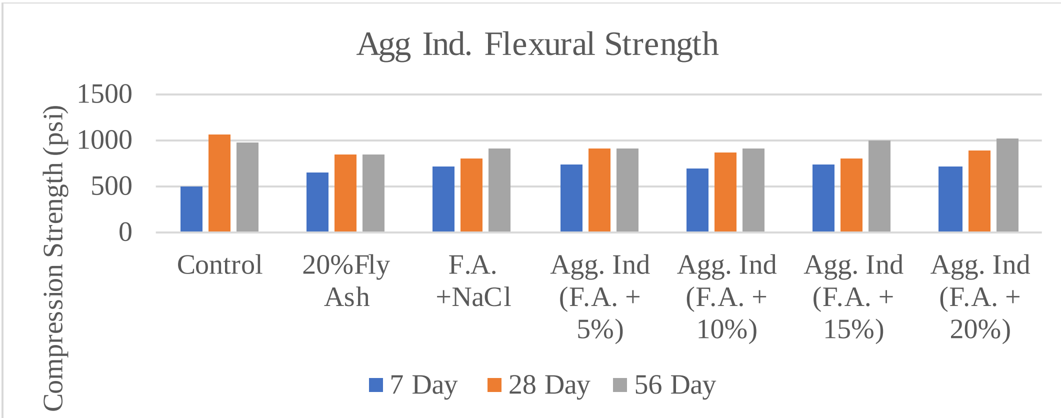


Figure 11. Flexural Strength for Aggregate Industries

The modulus of elasticity results are shown in Figure 12. The data showed to be just above the calculation. A 4000-psi compressive strength follows a 3.6x10^6 psi; however, the results obtained are above that estimate consistently. Each data point is an average of two samples. Equation one is an estimate for the modulus of elasticity; however, the results do not represent this equation too well. The figure also includes the Poisson's ratio as a line with the axis on the right expressing the value it curtails too. The Poisson's ratio is the ratio of the lateral deformation to the longitudinal deformation. It is used to determine shear modulus and can be used to find strains when there is a temperature change. The ratios are consistently between 0.18 and 0.21. When implementing the AMP, it did seem to increase the lateral deformation more; however, results from the other companies did not repeat this result as seen in Figure 12.

$$Ec = 33w_c^{1.5}\sqrt{f'c}$$ ***Equation 1***

Where:
E_c = Modulus of Elasticity (psi)

W_c= Unit Weight of Concrete (pcf)

f'c = Compressive Strength of Concrete (psi)

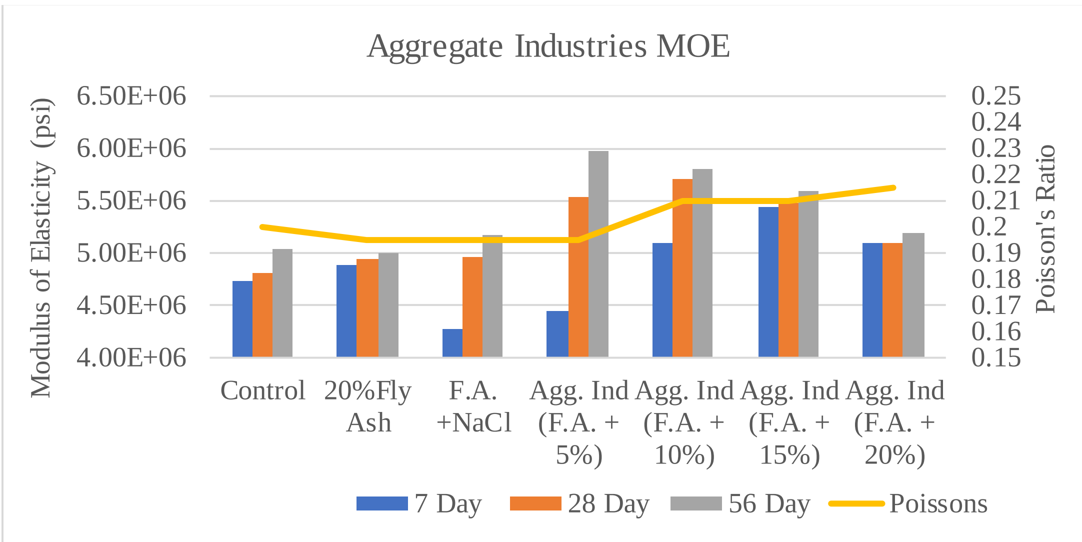


Figure 12. MOE Aggregate Industries

Table 5 depicts the average hardened properties for the Aggregate Industries mix in one table. There was minimal difference in compressive strength; therefore, there is a lack of evidence from the data to establish a difference in compressive strength when the AMP content was increased to 20% corroborating with previous research on de-icing chemicals. Adding 15-20% AMP appears to be the safest choice regarding hardened properties concerning flexural, compressive, and tensile strength; however, not much difference was revealed or expected. The air content indicated little impact on hardened properties since there was consistency between samples. The $NaNO_2$ results reinforced previous studies with a decrease in 28-day compressive strength (Craig and Wood, 1970). Unfortunately, there was not enough $NaNO_2$ to complete the tensile or flexural strength tests. Aggregate Industries had a sample of three cylinders regarding compressive strength, two for tensile, and one beam for flexural strength. The provided results are the average and statistical analysis shows the coefficient of variance (COV) to illustrate the consistency of the results. The closer to 0% the lower the variance between samples the less derivation from the mean. COV was found for samples with three or more samples; therefore, COV was not found for tensile or flexural strength.

Table 5. Hardened Properties for the Aggregate Industries Mix

Concrete Mixes	**Compressive Strength (psi) (COV)**			**Tensile Strength (psi)**			**Flexural Strength (psi)**		
	7 Days	**28 Days**	**56 Days**	**7 Days**	**28 Days**	**56 Days**	**7 Days**	**28 Days**	**56 Days**
Control	4192 (14%)	4802 (1.8%)	5540 (2.5%)	290	426	468	499	1069.5	974
F.A.	3806 (8.2%)	4860 (3.6%)	5600 (3.1%)	345	356	380	654	850	850
NaCl	3921 (4.2%)	4800 (6.3%)	5500 (1.3%)	275	370	390	717.5	803	909
5% AMP	3954 (3.4%)	4865 (4.6%)	5650 (3.6%)	334	449	390	730	921	904

10% AMP	3998 (9.1%)	4869 (6.0%)	5432 (3.7%)	327	425	400	701	870	908
15% AMP	4008 (3.7%)	4900 (5.2%)	5440 (2.4%)	360	410	447	732	809	1000
20% AMP	4051 (7.3%)	4854 (3.3%)	5500 (3.2%)	360	402	400	724	886	1020
NaNO2	3953 (9.3%)	4500 (5.3%)	4550 (4.9%)	X	x	X	X	X	X

4.2.2 Strata Mix

Figure 13 illustrates the compressive strength of the Strata mix. Similar to the Aggregate Industries mix the compression gained strength from settling to the 56-day break. From the 7-day break to the 28-day break, there was more strength gain consistently. The NaNO2 sample supported Craig and Wood's findings with a 20% reduction in compressive strength after 28 days, which was a repetition of the Aggregate Industries mix results. The compressive strength appeared to have decreased by 7-8% with the addition of 20% AMP as opposed to 15% AMP even when the fresh properties where similar between 15% and 20% AMP, although the Aggregate Industries mix did not provide the same findings. From the 7-day strength to the 28-day strength in comparison to the control, the early effects of fly ash can be observed. At the end of 28 days, the strength appears to have achieved up to the control's compressive strength. The results seem to mimic Aggregate Industries in compressive strength overall in terms of deicing impacts on compressive strength when not undergoing freeze-thaw conditions. It is interesting to note the decrease in compressive strength of 20% AMP in this mix, noting it can be recommended 15% AMP is the safest choice so far.

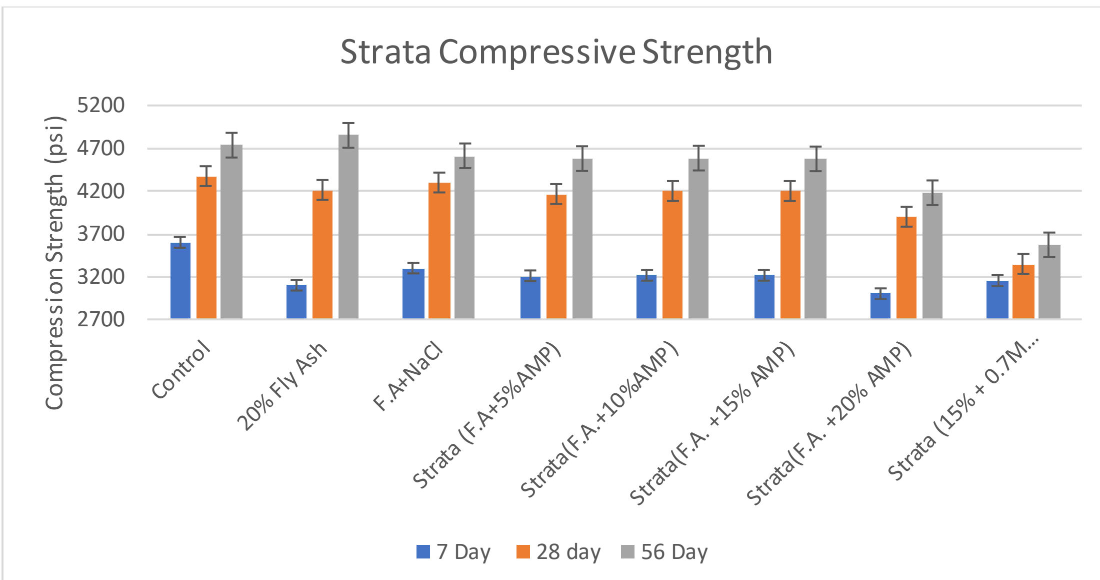


Figure 13. Strata Compressive Strength

Figure 14 illustrates the tensile strength of the Strata mix. The tensile strength followed similar patterns as fellow researchers and the previous tensile strength set. From about 8-10% of the compression strength and the increase in strength in curing times. The impact AMP had on average was about 50psi lower than the fly ash mixes and about 70psi underneath the control for the 56-day strengths. The 56-day decrease when exposed to deicers did have similarity to the Aggregate Industries mix.

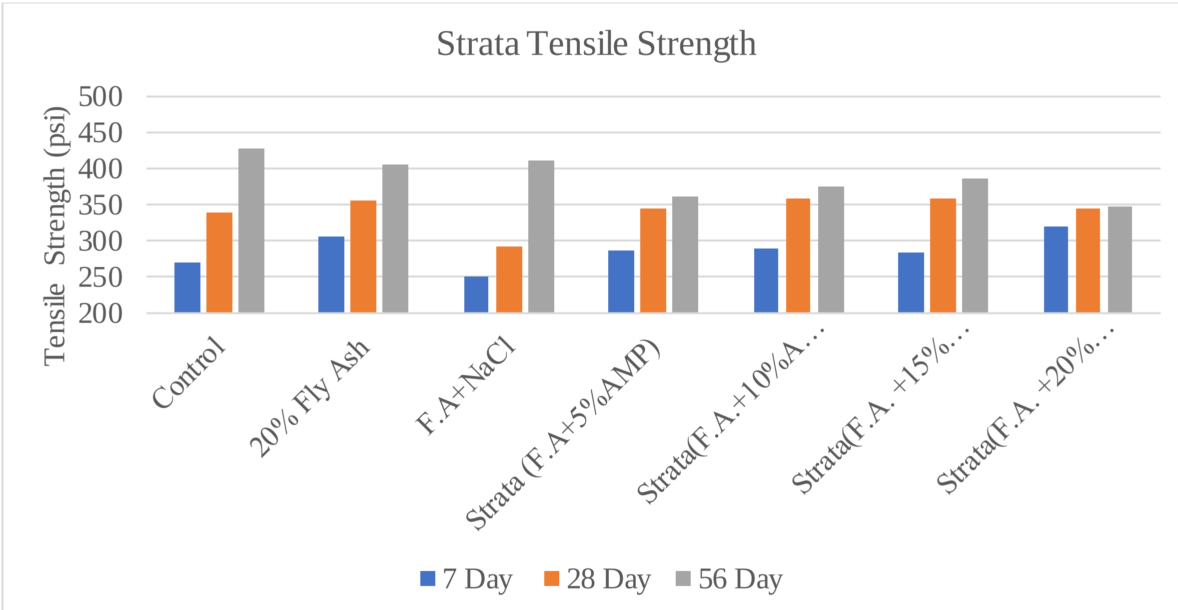


Figure 14. Strata Tensile Strength

The flexural strength of the Strata mix is illustrated in Figure 15. All the mixes were above the 650psi recommendation at 28 days; therefore, the mix is effective in following the recommendation for flexural strength. The flexural strengths obtained far exceeded minimum requirements and at times reached 20% of the compressive strength. The results so far have corroborated with Aggregate Industries' result and show consistency between deicers and fly ash.

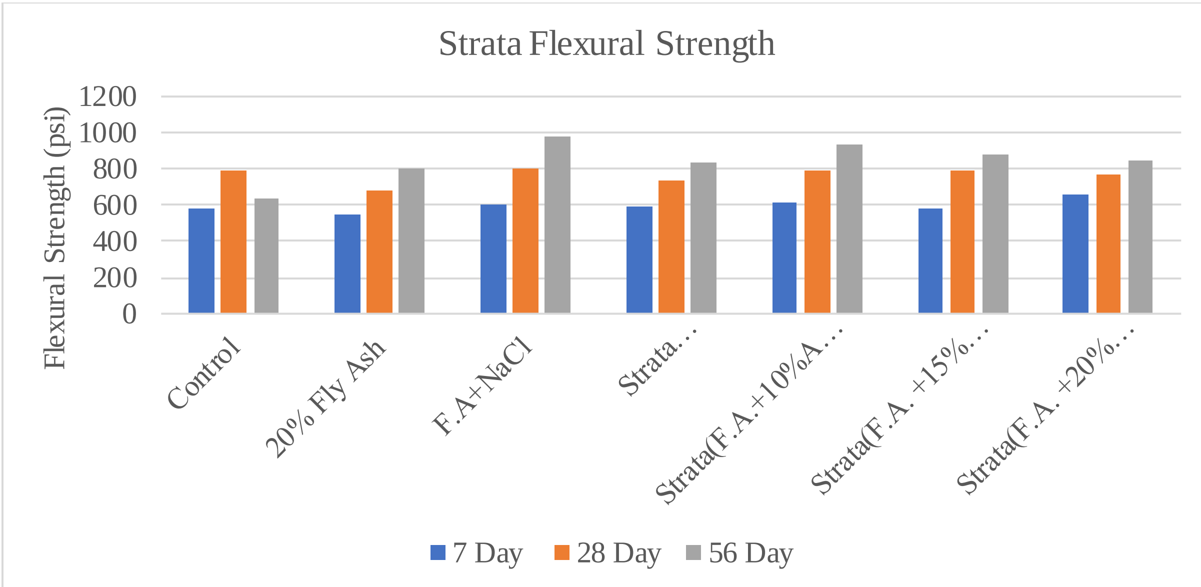


Figure 15. Strata Flexural Strength

The modulus of elasticity of the Strata mix is found in Figure 16. The results show the increase from the 28-day and the 56-day modulus is minimal. Similar to the other results in this project; the results do not follow the formula in Equation 1. Figure 15 reports the impact fly ash has on MOE and those deicers do not have a considerable impact on the MOE. The Poisson's ratio did not alter much from deicer to deicer ranging from 0.18-0.20. The value is the average of the 3 days and is placed as a value on the chart.

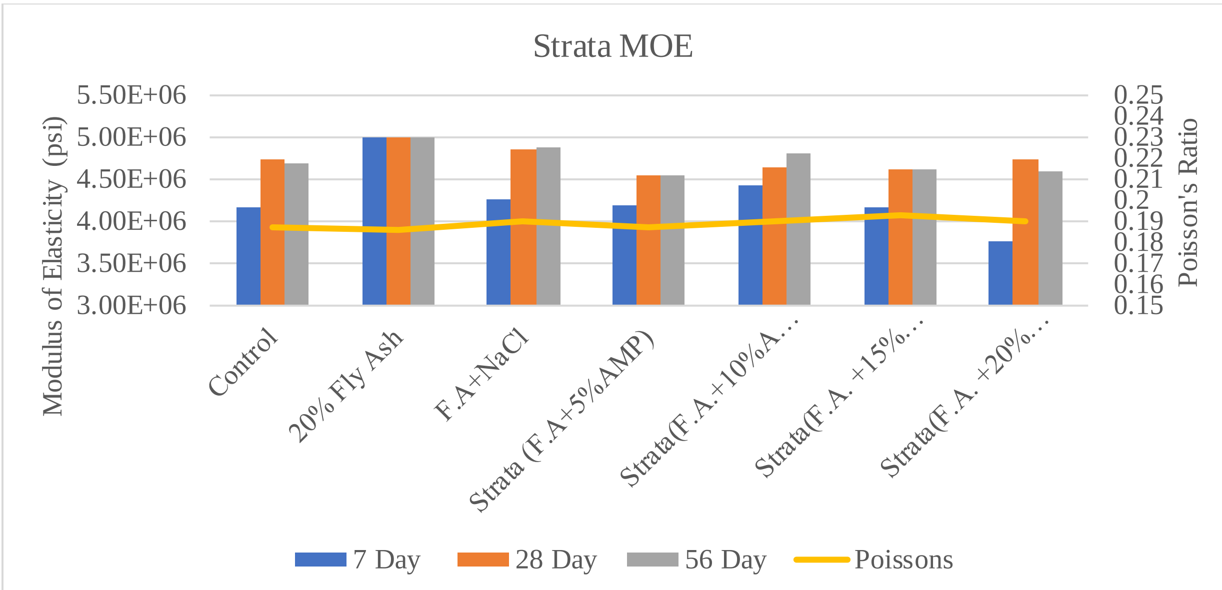


Figure 16. Strata Modulus of Elasticity

Table 6 depicts the hardened properties of the Strata mix. There was not enough $NaNO_2$ to perform the tensile or flexural strength tests at this time, similar to Aggregate Industries and Kost Industries. The results were similar to the results of the Aggregate Industries mix for 7 and 28 days. There was minimal difference in compressive strength between AMP percentage increases. The 5% differences in AMP percentages yielded a negligible difference in hardened properties except in compressive strength from 15% to 20% AMP; therefore, these differences demonstrate that there is little to no impact on compressive, tensile, and flexural strength. It should be noted the highest COV was found in the 20% AMP replacement, so there could have been an outlier in this set of data. Strata had the same number of samples as Aggregate Industries; therefore, COV was found for compressive strength since there were three samples. The COV was minimal in the tests found except for the 20% AMP where there was a higher deviation between samples; however, resulted in a decrease in compressive strength from 15% and further from the fly ash mix. The difference in compressive strength at 20% is an important factor to consider with Strata considering which AMP percentage to use even accounting for the higher COV.

Table 6. Hardened Properties for the Strata Mix

Concrete Mixes	**Compressive Strength (psi) (COV)**			**Tensile Strength (psi)**			**Flexural Strength (psi)**		
	7 Days	**28 Days**	**56 Days**	**7 Days**	**28 Days**	**56 Days**	**7 Days**	**28 Days**	**56 Days**
Control	3600 (1.4%)	4374 (2.6%)	4736 (1.6%)	270	339	427	581	792	650
F.A.	3107 (6.2%)	4213 (5.3%)	4850 (0.9%)	307	355	430	545	680	800
NaCl	3304 (4.6%)	4221 (8.1%)	4612 (2.8%)	250	378	435	601	787	980
5% AMP	3213 (9.3%)	4165 (5.7%)	4579 (3.4%)	286	345	361	587	740	832
10% AMP	3212 (6.8%)	4203 (2.5%)	4585 (3.2%)	290	360	376	620	791	933
15% AMP	3217 (3.5%)	4210 (3.3%)	4576 (4.1%)	285	360	386	583	794	876

20% AMP	3150 (7.1%)	3900 (6.7%)	4180 (10.1%)	320	365	347	620	765	849
NaNO2	3155 (4.2%)	3350 (5.2%)	3571 (1.5%)	x	x	X	x	X	x

4.2.3 Kost

The compressive strength of the Kost aggregate mix is shown in Figure 17. However, absent the Kost fly ash mix, the curing time tends to catch up at 28 days for all the fly ash mixes. The introduction of fly ash does clearly show a reduction in the 7-day compressive strength, which is lower than the control. The compressive strength of the various deicers has risen, resulting in 15% AMP exhibiting the maximum strength during the curing periods. Unfortunately, there was not enough $NaNO_2$ to finish the Kost mix for curing periods after the scaling tests. With the evidence shown and previous research, it is evident that the implementation of $NaNO_2$ decreases the compressive strength by about 20% compared to the other deicers used.

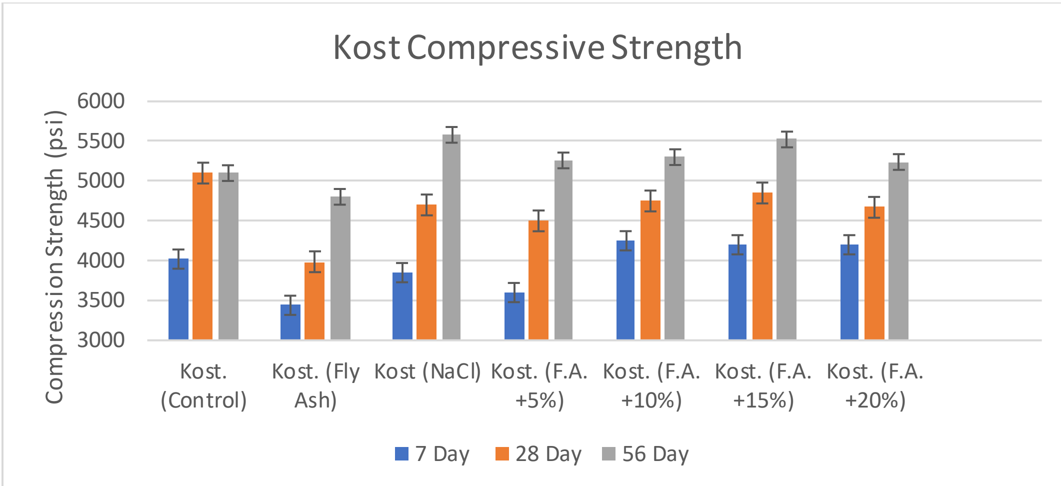


Figure 17. Kost Compressive Strength

Figure 18 shows the Strata tension results on the concrete mix. The tensile strength followed trends that were comparable to those of other studies and earlier tensile strength sets. For the 56-day strengths, the effect of AMP was on average around 50 psi lower than the fly ash mixes and about 70 psi lower than the control. There was no outlier in the data; therefore, the results are consistent throughout testing. There was no obvious evidence that the deicers had a considerable impact on the tensile strength by just the curing technique.

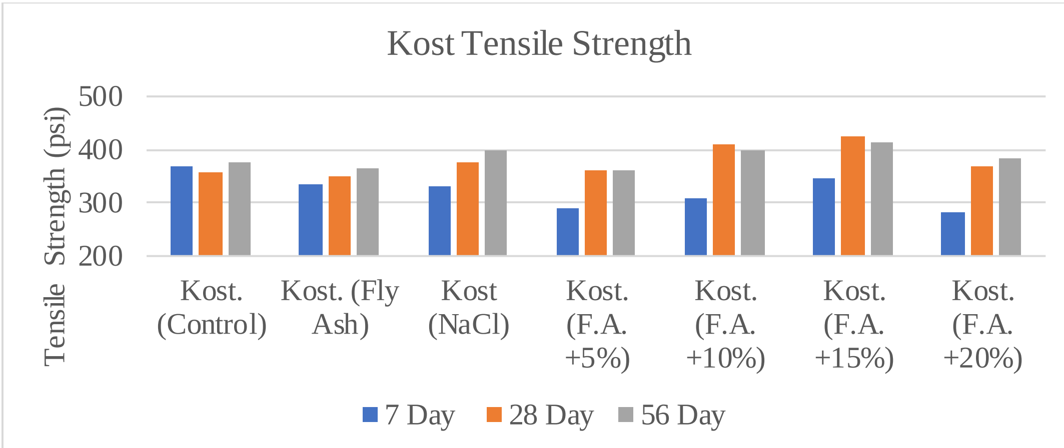


Figure 18. Kost Tensile Strength

Figure 19 illustrates the flexural strength of the Kost mix. At 28 days, all the mixes were over the recommended 650 psi level; as a result, the mix is successful in adhering to the flexural strength standard. The measured flexural strengths were significantly higher than the minimum requirements and regularly approached 20% of the compressive strength. The preliminary results demonstrate consistency across deicers and fly ash and agree with the results from Aggregate Industries and Strata Corporation.

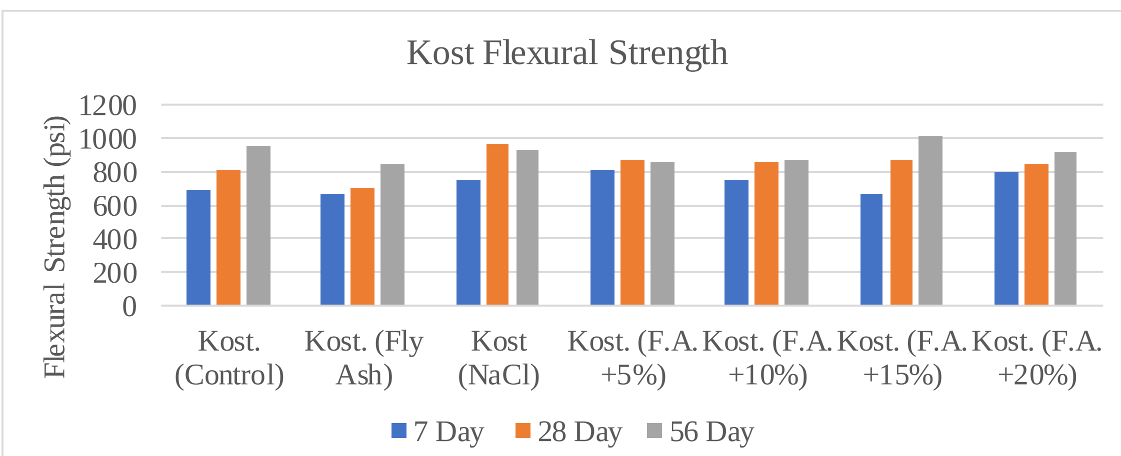


Figure 19. Kost Flexural Strength

Figure 20 illustrates the Kost Modulus of Elasticity. The 56-day MOE results from 4.6-5.0x10^6 psi. The 5% AMP exhibited lower results than other deicers, however, the researchers would caution that only two samples were examined, and the outcomes from the other samples and tests remained consistent, implying that the 5% AMP result might be an anomaly. The findings of this project, like the previous results, do not conform to Equation 1's formula. The consistency between projects shows a fairly appropriate range to make comparisons; however, noting there is a small sample size for MOE.

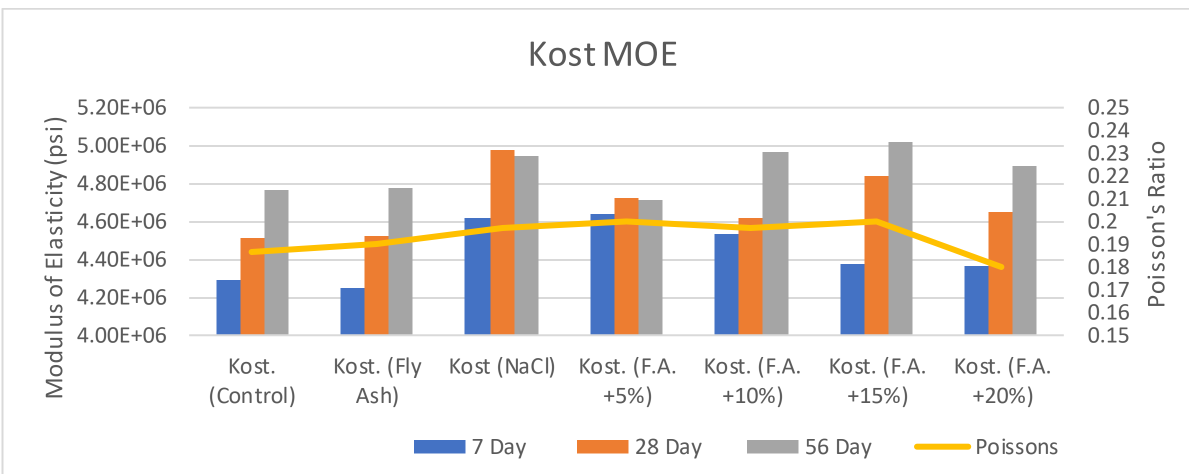


Figure 20. Kost Modulus of Elasticity

Table 7 depicts the hardened properties of the Kost mix. The results were similar to the results of the Aggregate Industries mix. There was more difference between 5% AMP and 10% AMP compared to the other tests; however, the trend continues throughout the companies. The 5% differences in AMP percentages yielded a negligible difference in hardened properties; therefore, these differences demonstrate that there is little to no impact on compressive, tensile, and flexural strength. The impact of air content could explain the differences between 15 and 20% AMP; however, the differences should be noted repeating similar results to Strata. Kost had the same number of samples as Aggregate Industries and Strata; therefore, COV was found for compressive strength since there were three samples.

Table 7. Hardened Properties for the Kost Mix

Concrete Mixes	Compressive Strength (psi) (COV)			Tensile Strength (psi)			Flexural Strength (psi)		
	7 Days	28 Days	56 Days	7 Days	28 Days	56 Days	7 Days	28 Days	56 Days
Control	4020 (3.4%)	5040 (8.6%)	5100 (2.6%)	370	357	375	695	816	960
F.A.	3440 (7.2%)	3987 (5.4%)	4802 (3.3%)	335	350	365	665	703	845
NaCl	3850 (7.3%)	4703 (6.1%)	5580 (9.2%)	330	377	400	756	970	936
5% AMP	3600 (8.5%)	4540 (6.2%)	5259 (5.3%)	290	360	363	809	876	864

10% AMP	4250 (9.6%)	4750 (6.7%)	5302 (4.5%)	310	410	400	755	853	864
15% AMP	4201 (7.4%)	4853 (3.3%)	5522 (4.5%)	346	426	412	672	872	1014
20% AMP	4217 (6.1%)	4670 (4.6%)	5239 (3.4%)	284	370	385	803	845	918
NaNO2	3539 (4.8%)	3945 (4.3%)	x	X	x	X	x	X	x

4.3 Concrete Freeze-Thaw Results and Scaling Results

Figure 21 depicts the relative dynamic modulus of elasticity for the control and 20% fly ash replacement for Aggregate Industries. The researchers decided to use only the 100% cement (control) and the moist cured 20% fly ash sample due to the decreased freezing point of water caused by the NaCl and AMP solution. The freeze-thaw following ASTM C-666 used water ranging from temperatures 0°F- 40°F. The eutectic point of a NaCl brine is -6°F or -16.6°F following Drebushchak (2017) with a 23.3% NaCl addition; therefore, the solution will not freeze at this temperature, which conforms to the ASTM C-666 standard. The impact deicers have on concrete will be tested following a modified version of the scaling standard BNQ-2621.

4.3.1 Aggregate Industries

The relative dynamic modulus of elasticity was recorded after two different samples were used, then the results were averaged to determine the modulus values after each cycle was completed. The concrete's frequency and mass were tested every 36 cycles, and the results were noted after each cycle to calculate the dynamic modulus of elasticity based on the concrete's original frequency before exposure to a freeze-thaw environment. The results indicated that using 20% fly ash decreased the resistance to the dynamic moduli at 288 cycles, from 87.2% to 95.9 strictly following the ASTM standard. Two samples were used to come to an average for the results. It is important to highlight that the outcomes complied with the ASTM standard and that fly ash has been proven to increase the resilience of concrete exposed to freeze-thaw. When compared to other tests that strictly followed the ASTM standard, the tests may be useful. A hardened air void analyzer could be used to augment the results.

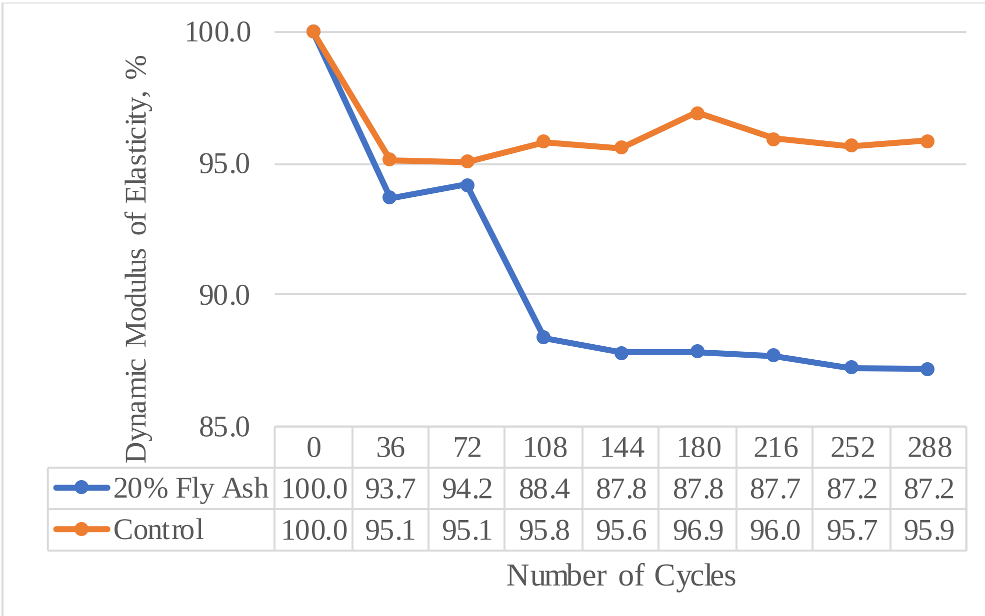


Figure 21. Aggregate Industries Relative Dynamic Modulus of Elasticity vs. Number of Cycles

Table 8 lists the results of 288 freeze-thaw cycles following ASTM C-666 for Aggregate Industries. The control with 100% cement did not deteriorate much compared to the class C fly ash. There was very little mass loss when subjected to freezing and thawing with Portland cement, and a 2.1% mass loss with 20% fly ash replacement. This data agrees with other results obtained by other researchers (Shon et al., 2018).

Table 8. Aggregate Industries Freeze-Thaw Mass Loss and Durability Factor

Mix	w/(c+p)	Fresh Air Content	Mass Loss (lb)	Mass Loss (%)	F/T Durability Factor
Control	0.42	8.00%	0.24	1.36%	96%
20% Fly Ash	0.42	6.80%	0.42	2.1%	87%

4.3.2 Kost

Figure 22 illustrates the relative dynamic modulus of elasticity vs the number of cycles performed for Kost Industries. After employing two separate samples, the relative dynamic modulus of elasticity was measured. The findings were then averaged to get the modulus values for each cycle. Every 36 cycles, the concrete's frequency and mass were measured, and the findings were recorded after each cycle. Based on the concrete's initial frequency before being exposed to a freeze-thaw environment, the dynamic modulus of elasticity could then be calculated. The findings showed that the resistance to the dynamic moduli at 288 cycles reduced when 20% fly ash was used, going from 89.9% to 97.0% precisely adhering to the ASTM norm.

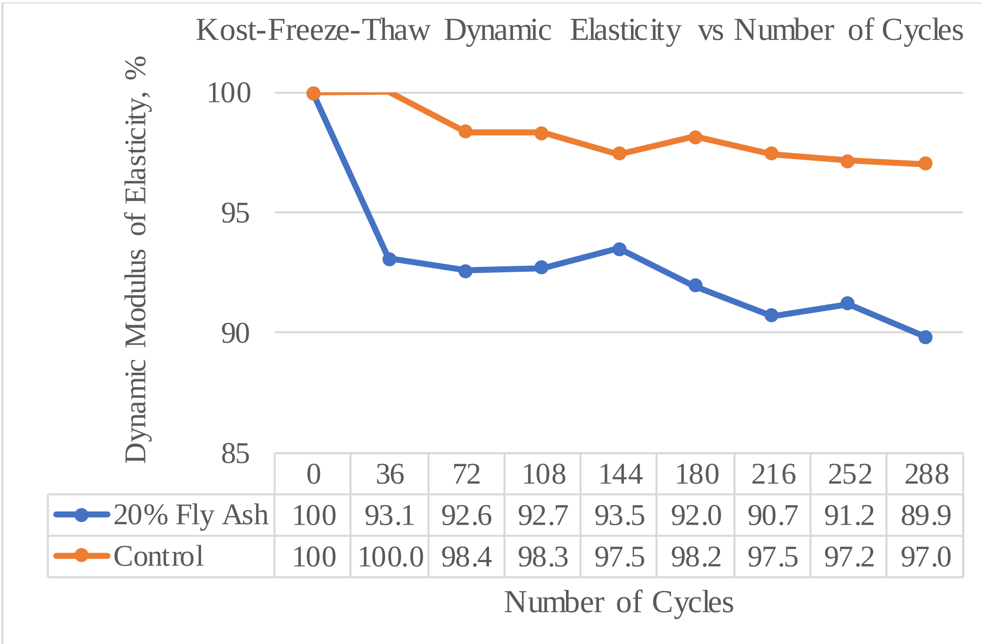


Figure 22. Kost Relative Dynamic Modulus of Elasticity

Table 9 is a depiction of the properties and the durability of the concrete. Fly ash resulted in a higher mass loss at a .38% higher mark than the 100% Portland cement control. The results for the durability factor corroborate with the mass loss of the data.

Table 9. Kost Durability Table for Freeze-Thaw

Mix	w/(c+p)	Fresh Air Content	Mass Loss(lb)	Mass Loss	F/T Durability Factor
Control	0.42	6.40%	0.19	1.12%	97.00%
20% Fly Ash	0.42	5.30%	0.324	1.50%	89.90%

4.3.3 Strata

Figure 23 is the illustration of Strata's relative dynamic modulus of elasticity. The relative dynamic modulus of elasticity was determined using two different samples. The modulus values for each cycle were then calculated by averaging the results. The frequency and mass of the concrete were tested every 36 cycles, and the results were recorded after each cycle. The dynamic modulus of elasticity could then be estimated based on the initial frequency of the concrete before being subjected to a freeze-thaw environment. The results showed that using 20% fly ash decreased the resistance to the dynamic moduli at 288 cycles, going from 91.2% to 95.5% precisely complying with the ASTM requirement.

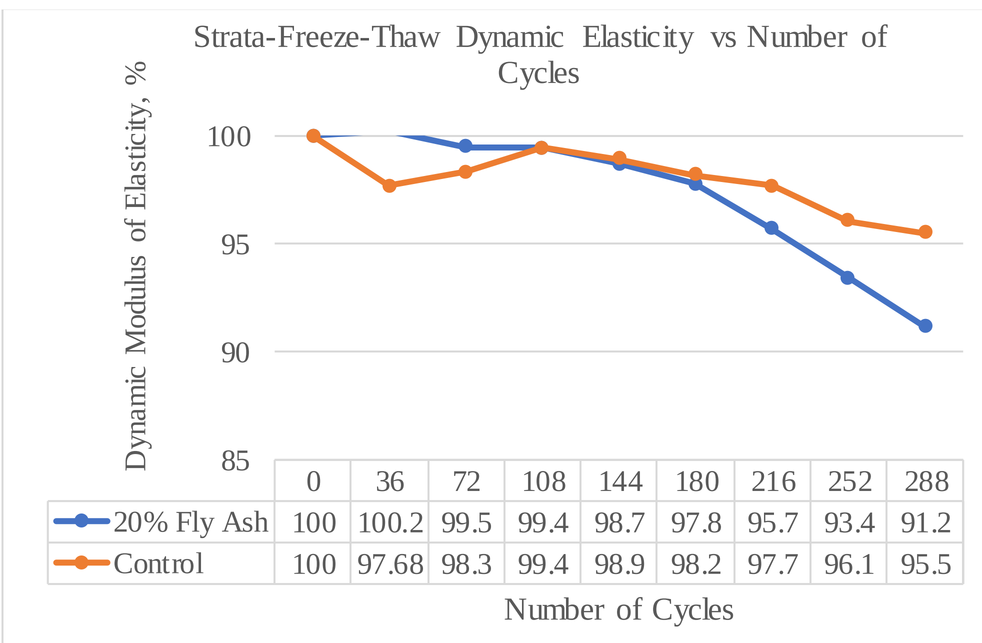


Figure 23. Strata Relative Dynamic Modulus of Elasticity

Table 10 is the results of the durability of the concrete after freeze-thaw cycles. In comparison to the class C fly ash, the control with 100% cement did not degrade as much. When Portland cement was frozen and thawed, there was relatively little mass loss; however, 20% fly ash replacement resulted in a 3.26% mass loss.

Table 10. Strata Freeze-Thaw Durability

Mix	w/(c+p)	Fresh Air Content	Mass Loss(lb)	Mass Loss	F/T Durability Factor
Control	0.42	7.00%	0.214	2.60%	95.50%
20% Fly Ash	0.42	4.90%	0.537	3.26%	91.20%

4.4 Scaling Results

Scaling was tested following the Canadian standard BNQ-2621-900; however, the team decreased the freezing temperature from 0°F to -20°F since the eutectic point is -6°F to -17°F. Instead of the 3% saline solution given in the standard, the solution will be the solution being tested for NaCl, 5% AMP, 10% AMP, 15% AMP, 20% AMP, and the NaNO2 solution. A concrete slab with a volume of 11"x9"x3" (280mmx230mmx75mm) was cast with a geotextile fabric underneath to aid in drainage. An impermeable dike was caulked to the sides of the concrete slab to account for the top ¼" of the concrete surface that was submerged in the solution. There was a 7-day pre-saturation using the dike after 14 days of moist curing and 14 days of air curing. Mass loss and surface condition were evaluated after 5, 10, 15, 25, and 56 days. A visual evaluation was conducted using a 1-5 rubric, where 1 represents no damage and 5 represents severe damage, where the aggregate is visible over the entire surface. This test is time intensive; therefore, scaling tests can take up to three months to fully complete.

4.4.1 Aggregate Industries

Table 11 depicts the surface condition of the concrete slab used for each solution on the day tested for Aggregate Industries. There was little difference between the solutions. None of the results exhibited a complete loss of paste on the surface. An addition of 20% AMP resulted in the highest deterioration compared to the other samples tested. Some of the aggregates were visible as the tests progressed; however, we could not establish a clear correlation between AMP increases. The solution used a 0.7M ratio of NaCl/$NaNO_2$ and the team used a 15% AMP mix because that is currently in use by the City of Grand Forks. There is a minimal indication, based on the Aggregate Industries mix, that the application of the inhibitor results in more damage to concrete when compared to the other deicers.

Table 11-Surface Condition (1-5 scale) of the Aggregate Industries Mix

	NaCl	5% AMP	10% AMP	15% AMP	20% AMP	$NaNO_2$
5 Day	1	1	1	1	1	1
10 Day	1	2	1	2	2	2
15 Day	2	2	2	3	2	3
25 Day	2	2	3	3	4	3
56 Day	3	3	3	3	4	3

Table 12 provides the mass loss of the Aggregate Industries mix. The sample was weighed on top of a surface analysis after adhering to the BNQ standard for the day tested, and the weights of the samples are shown in Table 10. Chlorides and water have easier access to the aggregates, leading to quicker deterioration because the coarse aggregate becomes exposed. As mentioned in the literature review, salt scaling is aesthetically displeasing due to coarse aggregate exposure and increases the scaled specimen surface's sensitivity to the penetration of fluids and detrimental ions such as chloride (Valenza & Scherer, 2007). The mass loss in Table 10 reveals the surface loss; hence, the more significant the mass loss, the greater the probability that ingress has taken place and has begun to enlarge the volume of the liquid in the pores of the concrete due to the freezing of the liquid.

Table 12. Mass Loss of Scaling Aggregate Industries

Column1	NaCl	5% AMP	10% AMP	15% AMP	20% AMP	NaNO2
5 Day	22.34	23.63	24.76	24.16	24.76	23.65
10 Day	22.34	23.66	24.64	24.11	24.66	23.60
15 Day	22.12	23.65	24.64	24.04	24.34	23.47
25 Day	22.16	23.35	24.44	23.77	24.13	23.35
56 Day	22.01	23.16	24.18	23.45	23.56	22.99
Mass Loss (%)	1.49	2.00	2.16	2.92	4.84	2.83

4.4.2 Strata

Table 13 is the interpretation of the Strata mixes surface scaling. Just like the Aggregate Industries, the visual interpretation follows a 1-5 scaling where 1 is little to no surface scaling to 5 where there is severe scaling on the surface of the concrete. There seem to be similar results from the previous tests; however, 15% AMP at 56 days did scale a little more receiving a score of 4. The $NaNO_2$ test is not yet complete, anticipation of completion is expected the 1st week of May 2023. The findings did correspond to the pattern shown by the Aggregate Industries result, where scaling was affected by a rise in AMP percentage when it reached 15-20% replacement for NaCl.

Table 13. Scaling Results Strata

	Surface Condition(1-5)					
	NaCl	5% AMP	10% AMP	15% AMP	20% AMP	NaNO2
5 Day	1	1	1	1	1	1
10 Day	1	1	1	1	1	2
15 Day	2	1	2	2	2	2
25 Day	2	2	2	3	4	3
56 Day	3	3	3	4	4	

Table 14 is the table for masses on each respective day and the cumulative mass loss percentages for each deicer. There appeared to be at least a 4% mass reduction, which would be seen as a visual rating of 4.

Table 14. Strata Mass Loss from Scaling Tests

Column1	NaCl	5% AMP	10% AMP	15% AMP	20% AMP	NaNO2
5 Day	21.68	23.93	24.72	24.47	23.93	26.61
10 Day	21.54	23.86	24.64	24.41	23.93	26.40
15 Day	21.45	23.80	24.64	24.34	23.56	26.29
25 Day	21.36	23.66	24.44	24.13	23.23	26.22
56 Day	21.07	23.55	24.18	23.25	22.96	
Mass Loss (%)	2.82	1.61	2.16	4.96	4.05	1.47

4.4.3 Kost

Table 15 illustrates the visual scaling results for the Kost mix. The 56-day mix results will be ready the 1st week of May 2023. The trend seems to continue that up to 15% of AMP causes similar damage to the surface. When 15% AMP is replaced there seems to be a slight decrease in durability. This could be due to the increased amount of Magnesium Chloride or Calcium Chloride in the AMP. As mentioned in the literature review, Deicers can affect the durability of concrete by limiting air spaces, crystallization, increasing saturation, exposing concrete surfaces to heat shock, and perhaps escalating osmotic pressures, as was already indicated (Li et al. 2016; Richardson, n.d.; Xie et al., 2017). The increase in the salts can cause an increase in thermal shock or expansion; therefore, resulting in higher scaling with more AMP.

Table 15-Scaling Results Kost

	Surface Condition(1-5)					
	NaCl	5% AMP	10% AMP	15% AMP	20% AMP	NaNO2
5 Day	1	1	1	1	1	1
10 Day	1	1	1	1	2	1
15 Day	2	1	2	2	2	2
25 Day	2	2	2	3	3	3
56 Day						

Table 16 is the mass loss of the scaling beams for Kost Industries. Kost seemed to absorb some of the liquid initially, then start to lose some of the surface paste for 10-15 days in the freezing and thawing conditions. The 56-day results will be finished the 1st week of May.

Table 16. Kost Mass Loss Scaling

Column1	NaCl	5% AMP	10% AMP	15% AMP	20% AMP	NaNO2
5 Day	26.46	26.14	27.12	26.36	24.90	24.50
10 Day	26.54	26.23	27.18	26.44	25.02	24.51
15 Day	26.52	26.14	27.25	26.36	24.97	24.61
25 Day	26.10	26.08	27.08	26.09	24.29	24.30
56 Day						
Mass Loss(%)	1.36	0.23	0.13	1.01	2.44	0.84

4.5 Relationship between Durability and Air Content

4.5.1 Aggregate Industries

Table 17 is the comparison between the surface condition of scaling beams and the fresh air content and SAM number. The air void spacing and the air content is well known to be important in resistance to freezing and thawing and surface scaling. Although there are not many variations in air content and SAM number between mixes, if the difference is significant enough, it could have an effect. Mix-to-mix air content ranges from 4.6% to 6.5%. It is vital to remember that the lower the air content, the higher the scaling appeared to be. It also happens to contain the most AMP. The resistance to freeze-thaw did appear to be impacted by the mixture of higher deicers and lower air content. The durability of concrete may suffer from the interaction of insufficient spacing, low air content, and high levels of AMP.

Table 17. Aggregate Industries Fresh Air Content and Scaling Results Interpretation

			Surface Condition				
Mix	**Air Content(%)**	**SAM**	**5 Day**	**10 Day**	**15 Day**	**25 Day**	**56 Day**
F.A+NaCl	6.5	0.39	1	1	2	2	3
F.A+5%AMP	5.5	0.45	1	2	2	2	3
F.A.+10%AMP	6	0.45	1	1	2	3	3
F.A. +15% AMP	6	0.4	1	2	3	3	3
F.A. +20% AMP	4.6	0.44	1	2	2	4	4
NaNO2	5.8	0.39	1	2	3	3	3

4.5.2 Strata

Table 18 illustrates the comparison between air content, SAM number, and the visual scaling interpretation. The mix design has shown there was little difference between air content and SAM for each respective mix; therefore, it can be difficult to make concrete judgments on the impact the small differences in air content or SAM number make on scaling. The air content was between 4.8% and 5.3% and a SAM number ranging from 0.39-0.45 throughout Strata's mixes. The surface condition did not vary much due to the small differences in air or SAM, but mostly from the deicing agents as seen from the increase in AMP percentage. A petrographic analysis could augment the results of how small differences in air content of SAM number can have on surface scaling and mass loss.

Table 18. Strata's Air Content Surface Scaling Comparison

			Surface Condition				
Mix	**Air Content(%)**	**SAM**	**5 Day**	**10 Day**	**15 Day**	**25 Day**	**56 Day**
F.A+NaCl	5.1	0.45	1	1	2	2	3
F.A+5%AMP	5.4	0.44	1	1	1	2	3
F.A.+10%AMP	5.1	0.43	1	1	2	2	3
F.A. +15% AMP	5.3	0.41	1	1	2	3	4
F.A. +20% AMP	4.8	0.42	1	1	2	4	4
NaNO2	5.1	0.39	1	2	2	3	

4.5.3 Kost

Table 19 is the current results of the visual interpretation of scaling and the fresh air content and SAM number for Kost. The scaling results will be finished in May; however, similar comparisons can be made. The air content ranged from 4.2% to 5.5% and the SAM number ranged from 0.26 to 0.32. The pattern seems to be that the deicing agent had an effect on the surface but the slight difference in air content did not significantly affect the outcomes. To ascertain the effect that the spacing between hardened and fresh air voids can have on the durability of concrete, a petrographic examination can be used in addition to the SAM number.

Table 19. Kost Scaling and Air Content Comparison

			Surface Condition				
Mix	**Air Content(%)**	**SAM**	**5 Day**	**10 Day**	**15 Day**	**25 Day**	**56 Day**
F.A+NaCl	4.2	0.28	1	1	2	2	

F.A+5%AMP	4.8	0.29	1	1	1	2	
F.A.+10%AMP	5.5	0.26	1	1	2	2	
F.A. +15% AMP	4.8	0.32	1	1	2	3	
F.A. +20% AMP	5.5	0.26	1	2	2	3	
NaNO2	5.2	0.21	1	1	2	3	

Chapter 5 DISCUSSIONS, CONCLUSIONS, RECOMMENDATIONS, AND FUTURE WORK

5.1 Discussions

The project's significance provides a solution to the question of what effects deicing agents have on the mechanical strength and durability of concrete. Implementing NaCl has long been known to be the cheapest deicing agent available due to the supply and how inexpensive it is to buy. The city of Grand Forks implements a 15% AMP solute in a salt solution due to the recommendation of the supplier. This research aims to determine the optimum AMP amount for the roadways in Grand Forks, North Dakota, and its suppliers. The researchers decided to implement a corrosion inhibitor to test if the inclusion will have an impact on the freeze-thaw durability of concrete, and from the results, it did not have a sizable impact on the resistance of concrete to scaling. The researchers sought to replicate the mixes to create a more equivalent mix to the concrete in the field and obtained aggregates from local businesses to simulate Grand Forks' surroundings as closely as feasible.

According to this study, the mechanical characteristics of concrete will not change much more when it cures in a deicer. 15% to 20% AMP replacement did tend to decrease in compressive strength using Strata and Kost aggregates; therefore, it is important to note the differences in compressive strength and the possible reasons including slight differences in fresh properties and higher differences in COV. The deicing bath was used, like a lime bath, which is intended to stop calcium carbonate from seeping out of the concrete. These deicers did not impact the mechanical properties against the use of a moist curing room considerably.

The deicing salts and augmented material did appear to affect how durable concrete was when subjected to freeze-thaw. The durability factor did drop from 7–12% when fly ash was included in Portland Cement by 20% following ASTM C-666. In contrast, field studies show that fly ash supports freeze-thaw more effectively. The project followed ASTM C-666; therefore, the samples can be valuable when compared to other samples that used the same test procedure and not necessarily in the field.

Scaling followed BNQ-2621 and the test is used due to the ASTM standard being withdrawn in 2021. The BNQ standard followed some different protocols than the ASTM standard to provide a more realistic result for fly ash. The researchers did modify some of the procedures to ensure the deicers froze and included different days of testing to 5,10,15, 25, and 56 days. We can obtain a decent idea of the effect the deicers have on concrete by analyzing the data, which shows that the standard is more suitable than the ASTM standard from several different publications. When increasing to 15-20% AMP, the rate of mass loss did accelerate according to Tables 12,14, and 16. The visual interpretation did closely follow the mass loss when exposed to the surface of the concrete. Where 20% had the highest impact on the visual rating closely followed by 15%.

The implementation of $NaNO_2$ did predictably result in a decrease in compressive strength and the tests show a decrease of about 20% after 56 days compared to just the deicer. When undergoing scaling tests, there is little proof that the implementation of $NaNO_2$ with 15% AMP decreased the durability of concrete more; therefore, following the BNQ-2621 standard, there was no major impact of implementing $NaNO_2$. It was difficult for the researchers to obtain the inhibitor at a scale and a good price; therefore, it is difficult to recommend this chemical unless circumstances change.

5.2 Conclusions

The following conclusions can be made based on this study:

- Introducing fly ash had a moderate impact on concrete durability, including mass loss and relative modulus of elasticity according to ASTM C-666 (Figure 20-22).
- The results indicated that fly ash impacts compression strength at seven days but will reach Portland-like cement strength at 56 days (Tables 5-7).
- Using NaCl and AMP had little impact on compressive strength compared to $NaNO_2$ (Tables 5-7, Figures 8-19).

- Introducing $NaNO_2$ resulted in a reduction in 28-day compressive strength (Tables 5-7).
- Scaling results illustrate that the increase in AMP has little impact on surface condition until 15-20% AMP replacement for NaCl (Table 11-16).
- The implementation of $NaNO_2$ decreased compressive strength; however, there are no obvious signs that it impacted the durability or soundness of aggregates (Table 11-16, Tables 5-7).

5.3 Recommendations

Based on this study, the following recommendations can be made:

- Deicer use is critical for public safety. Adding AMP to NaCl will augment the material and aid in binding to the road's surface.
- Introducing NaCl and AMP had little to no impact on hardened properties; therefore, the researchers recommend using 10-15% AMP with the 23.3% NaCl solution due to the loss of compressive strength at 20% and the scaling results.
- After the freeze and thaw tests, the researchers recommend taking the ASTM C666 test results with a grain of salt, as the results have shown that fly ash will decrease durability. It is well known that fly ash has been seen to increase durability in the field. The results can be used to compare to other research using the same test.

- The use of $NaNO_2$ to reduce corrosion resulted in a reduction in the hardened properties, but the durability of the concrete was unaffected when exposed to $NaNO_2$.

5.4 Future Work:

The researchers would like to highlight some potential ideas for this project or different ideas stemming from this work.

- Implementation of nano-clay, synthetic fibers to make up for the loss of hardened properties due to $NaNO_2$.
- Use of organic bonding agents instead of AMP. Such suggestions include beet juice, cheese brine, and pickle juice as a substitution for AMP.
- Use of ASTM C457 to supplement data caused by freeze-thaw and to enhance the accuracy of the SAM meter.

Chapter 6 REFERENCES

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