Chemistry and Performance of Supplementary Cementitious Materials (SCMs) for Wisconsin Concrete Pavement

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16. Abstract

An extensive testing program, including materials characterization and concrete performance evaluation, was performed. Performance included materials characterization and concrete performance. A total of ten materials were studied. Characterization included chemical composition, XRD, density, setting time, water requirement, particle size, a modified version of the strength activity index, a modified version of the foam index, and reactivity. The performance of concretes containing these SCM and ASCM, as well as a concrete containing a combination of liquid SCM was evaluated and compared to a control mixture. Among the properties were box test, compressive and flexural strength, shrinkage, electrical resistivity, and freeze-thaw resistance.

Based on the results of this study, several recommendations were provided, including the implementation of the modified SAI, the use of reactivity tests to screen new materials, the increase of the maximum SAM number, and the increase of the maximum LOI to match ASTM C618.

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Executive Summary

This study investigated the performance of supplementary cementitious materials (SCMs) and alternative supplementary cementitious materials (ASCM). Performance included materials characterization and concrete performance. A total of ten materials were studied. Characterization included chemical composition, XRD, density, setting time, water requirement, particle size, a modified version of the strength activity index, a modified version of the foam index, and reactivity. Concrete performance included slump, the box test, air content, SAM, compressive and flexural strengths, freezing and thawing resistance, surface resistivity and length change due to shrinkage.

Results showed that some of these materials (Micron3, Opus, PozzSlag, Liquid ASCM) either did not meet the requirements of ASTM specifications or did not meet the definition of the material in these specifications.

However, all concrete mixtures containing the SCM or ASCM in this study showed good performance, sometimes, at later ages, better than the control mixture, with exception of the liquid ASCM, which showed similar performance as the control.

The validity of the reactivity tests (ASTM C1897) was confirmed, and it was recommended to be implemented when evaluating a material with no performance history or alternative SCMs.

The modified SAI was found to be a good screening tool; thus, it was recommended for implementation.

The modified foam index was unable to correlate with concrete AEA demand but was found to be a good indicator of potential air entrainment problems.

Loss on ignition did not correlate with the AEA demand or with the foam index and the current 2% requirement for fly ashes is too restrictive.

Based on the findings of this study, recommendations were made to be included in the Wisconsin DOT specifications and a framework for the evaluation of ASCM was proposed.

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1.0 Introduction

Most transportation agencies use Supplementary Cementitious Materials (SCMs) in their concrete pavement mixtures, especially fly ashes, as a partial replacement for portland cement. SCMs are materials that react either with calcium hydroxide at high pH (pozzolanic) and/or with water at high pH (latent hydraulic), within a concrete mixture. SCMs contribute to long term performance, especially durability because they promote densification of the matrix. Additionally, SCMs reduce the carbon footprint of concrete.

The concrete industry faces two challenges: in one hand, the supply of “standard” SCMs is insufficient to fulfill the current needs, and on the other hand, an increasing demand to develop a more sustainable infrastructure, without sacrificing short- and long-term performances.

1.1. Current SCM Supply

It is estimated that the concrete production will increase by more than 50% through 2033 [1]. Consequently, the supply of SCM needs to increase accordingly. Fly ash is the most used SCM and currently the concrete industry uses around 52% of the fly ash produced. It has been suggested that the amount fly ash used, as a percentage of the amount produced, would need to reach a level of up to 70% to meet future demand [2].

On the other hand, the availability of fly ash meeting standards for its use in concrete has been decreasing in the past few years due to an increase in the use of natural gas, as well as the decrease in fly ash quality as a consequence of changes in the Environmental Protection Agency (EPA) standards for mercury and sulfur for power plants. The same EPA regulations are also forcing several coal-fired power plants to be deactivated since they cannot meet the EPA standards [2].

1.2. Possible Solutions

To help to meet the concrete industry’s growing need for SCMs, the use of other materials has come into play. Materials such as natural pozzolans (calcined clay, volcanic ashes, mine tailing, and vegetable ashes, etc.), and Alternative Supplementary Cementitious Materials (ASCMs) present an opportunity to address these challenges. Additionally, in 2023, ASTM approved, under ASTM C618-23[3], the use of other coal ashes in concrete, such as harvested landfill and ponded fly ashes; remediated ashes, and ground bottom ash.

According to ASTM C1709[4], ASCMs are inorganic materials that react pozzolanically or hydraulically, and beneficially contribute to concrete properties. These materials do not meet ASTM C618, C989/C989M, C1240 and C1866/C1866M. ASCMs can not only address the supply – demand issue and the growing interest in more environmentally friendly solutions but can potentially provide similar benefits to concrete performance as SCM do. The industry has decades of experience using SCMs but needs a guidance to understand the behavior of such materials, as well as to properly utilize it.

Despite the interest in using ASCMs in concrete, standardization for their use is still lacking. In 2011, ASTM published the first standard on ASCMs (ASTM C1709[4]), which is just an evaluation guide, and it does not address any specific requirements; it just refers to other specifications for different SCMs, such as ASTM C618-23 [3], C989/C989M-24[5] and C1240-20[6]. In 2019, ASTM published its first guide for harvesting coal combustion products (ASTM E3183[7]), but this standard fails to address any necessary processing to meet ASTM C618-23.

On a positive note, in 2021, CSA A3001[8] approved the use of co-mingled fly ash in concrete, and ASTM C618 is under ballot to allow its use, as well.

Moreover, there is an urgent need to develop a systematic protocol to be routinely used to assess and qualify the suitability of incorporating SCMs and ASCMs into concrete mixtures regardless of their types, source of origin, physical properties, or chemical composition, while ensuring that performance and durability are not compromised. This project addresses the use of conventional SCMs and ASCMs in concrete mixtures, as well as the necessary protocols to ensure concrete performance.

2.0 Research Need Statement

Currently, SCMs replace from 5 to 40 percent of cement mass in concrete mixtures, depending on the SCM involved. However, the basis for SCM limits are often empirical estimates that do not consider some important characteristics of the SCMs, such as chemical properties, mineralogy, and particle size distribution. The limits within ASTM or AASHTO standard specifications for these characteristics are sufficiently broad that variations from one source to another and sometimes within the same source may have a significant effect on the fresh and hardened properties of concrete for pavements[9]. WisDOT cement replacement limits are between 15% and 30%, with the exception of the class F fly ash. Class F fly ashes which source is not included in the approved products list (APL) are limited to a maximum replacement of 15% (Section 501.2.4.2.3 of [10]).

There is an urgent need to be able to use as many SCM and ASCM sources as possible to fulfill the industry's needs. Hence, the first step is proper evaluation of such materials in terms of characteristics that govern the concrete performance, followed by the proposal of protocols and the establishment of acceptable ranges for these characteristics. Figure 1 shows that some of the most important characteristics are the SCM reactivity and rate of reaction because they affect different concrete aspects of performance.

3.0 Research Objectives

The overall goal of this project is to correlate the SCMs and ASCMs characteristics to concrete short- and long-term performances in Wisconsin. For that, the objective is, in addition to the chemical and physical requirements already in the ASTM and AASHTO specifications, evaluate 1) the need to include other tests, and 2) propose other tests that can help predict the expected concrete performance. These objectives were accomplished by:

- Identifying traditional SCMs, non-traditional SCMs, and reclaimed ashes available to Wisconsin users,
- Establishing appropriate testing methodologies for SCM, ASCMs, as well as concrete containing SCM and ASCMs.
- Establishing acceptable test results ranges,
- Developing a database containing the chemical properties and other important characteristics of a variety of SCMs and ASCMs and along with corresponding concrete performance,
- Proposing revisions to WisDOT manuals, specifications, standards, and policies related to SCMs.

4.0 Literature Review

Before any material is used in concrete, its suitability is or should be verified using some established testing methodologies and criteria from standard specifications, as well as any specific requirement from the owner.

The following is a summary of specifications in the US, as well as some international specifications.

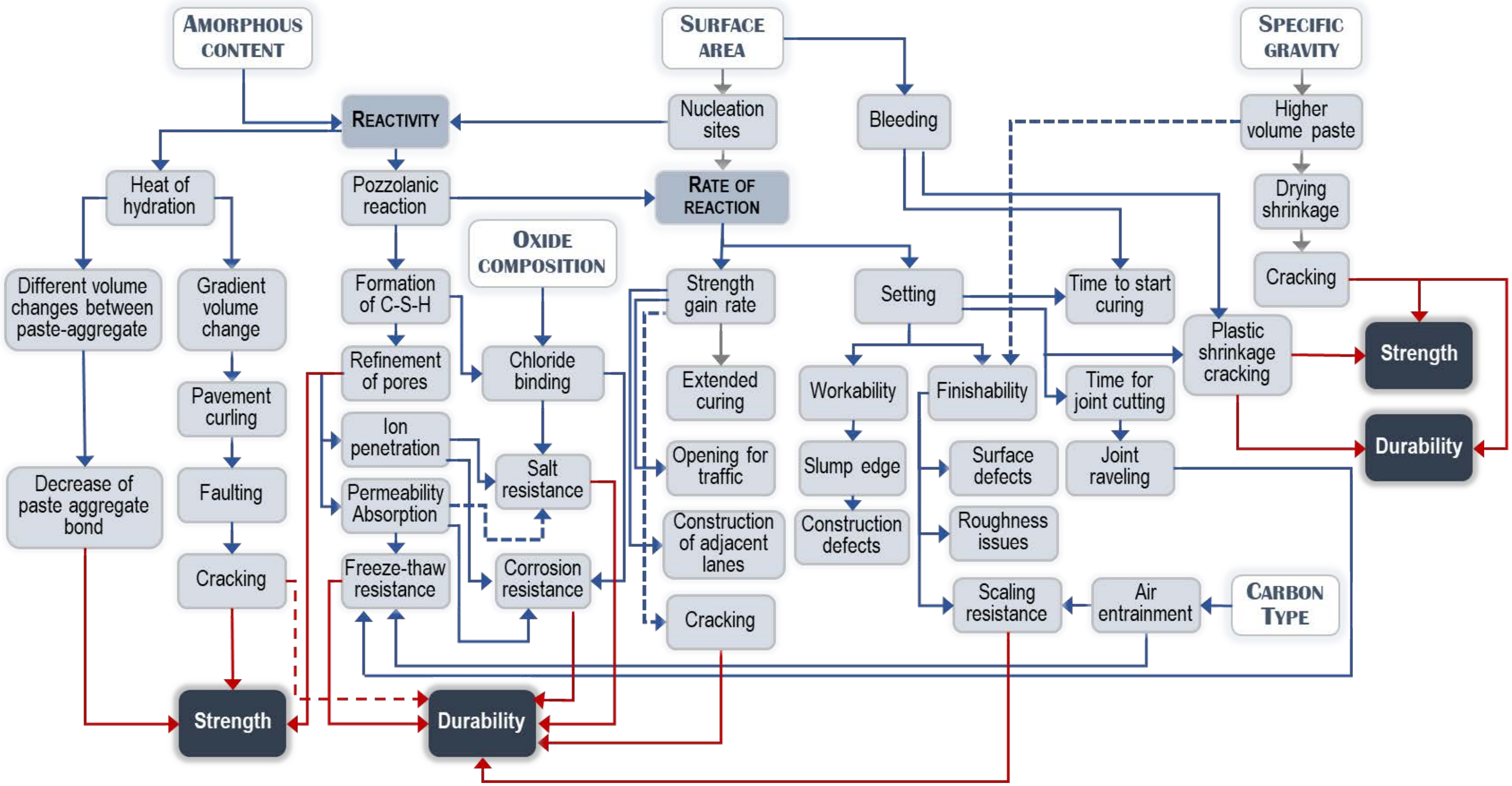


Figure 1 - SCMs main effects on concrete properties. Specific deterioration mechanisms such as alkali-silica reaction and sulfate resistance, among others. Red arrows indicate the ultimate effect on concrete strength and durability.

4.1. Industry and Government Perspectives

A series of interviews was conducted with individuals from industry and government. The goal was to assess the state-of-the-art and future use of SCMs and ASCMs, potential sources of these materials to supply Wisconsin, new materials approval process, and challenges and opportunities to implement ASCMs. A summary of the findings can be found in Appendix A.

Overall, it was pointed out that the shortage of known sources of fly ashes with good performance is a big concern in the concrete community but the lack of performance history and standards to properly characterize long-term performance complicates the acceptance of new materials or sources. Other reported challenges mentioned were uniformity and consistency

4.2. Standard Specifications in United States

Currently, ASTM has five standard specifications for supplementary cementitious materials: C618-23[3], for Coal Ash and Raw or Calcined Natural Pozzolan; C989/C989M-24[5], for Slag Cement; C1240-20[6], for Silica Fume; C1697-21[11], for Blended SCM; and C1866/C1866M-22[12], for Ground Glass Pozzolan. ASTM also has a Standard Guide for Evaluation of Alternative Supplementary Cementitious Materials, which provides guidance on how to evaluate the materials but does not provide any specific requirements.

Due to a harmonization agreement between ASTM and AASHTO, AASHTO has specifications that are very similar to those ASTM: AASHTO M 295-21[13], for Coal Ash and Raw or Calcined Natural Pozzolan; M 302-22[14], for Slag Cement; and M 307-22[15], for Silica Fume. AASHTO has not issued specifications either on blended SCM, or on ground glass pozzolan, however, it has a specification for High-Reactivity Pozzolans, AASHTO M 321-04 (2021)[16].

In general, these specifications are very prescriptive in nature, with chemical and physical requirements and some physical requirements that could be seen as performance based, such as the strength activity index (SAI), air content, water demand, and autoclave expansion. However, these characteristics may not necessarily be a measure of the expected performance in practice. For example, the intention of the SAI is not to predict strength of an SCM but it is used as the indirect means to assess the reactivity of a particular SCM.

Tables 1 and 2 show a summary of the requirements in these specifications. These specifications also have optional requirements that may include minimum amorphous content, increase in drying shrinkage, sulfate resistance, reduction in mortar expansion, and uniformity of AEA demand and density.

4.3. State DOTs Specifications

A summary of nine State DOTs specifications can be found in Appendix B. The minimum amount of cementitious materials for pavement application ranged from 450 lb/yd^3 to 600 lb/yd^3. The only State that didn't have a minimum cementitious content requirement in the area studied was Iowa.

The total maximum SCM allowed ranged from 30% to 50% of the total cementitious materials. The maximum percentage of cement replaced by fly ash varied between 20% and 30%, while the maximum slag cement varied between 30% and 50%.

Wisconsin Specification 501 allows a minimum cementitious content of 565 lb/yd^3, maximum w/cm = 0.45 and maximum SCM of 30%. A minimum of 500 lb/yd^3 of cementitious materials can be used, if the mixture is optimized.

If more than 15% of class F fly ash is to be used, only the sources in the approved product list (APL) can be used. Fly ashes must conform with ASTM C618/C618M with a 2.0% maximum loss on ignition, slag must conform with ASTM C989/C989M. Alternative supplementary cementitious materials are allowed and must comply with ASTM C1709.

Table 1 – Overview of Chemical Requirements in Different SCM Standard Specifications.

Chemical Requirements						
Requirements	ASTM					AASHTO M 321 High Reactivity SCMs
	C618	C989	C1240	C1697	C1866	
	Ashes, Natural Pozzolan	Slag Cement	Silica Fume	Blended SCM	Ground-Glass Pozzolan	
$SiO_2 + Al_2O_3 + Fe_2O_3$	Min*	-	-	Individual constituents shall comply with applicable specification	-	Min 75%
SiO_2	-	-	Min 85%		Min*	-
Al_2O_3	-	-	-		Max*	-
Fe_2O_3	-	-	-		Max 1.0%	-
CaO	For classification purposes	-	-		Max*	-
SO_3	Max*	-	-		Max 1.0%	Max 3%
Sulfide Sulfur	-	Max 2.5%	-		-	-
Moisture Content	Max*	-	Max 3%		Max 0.5%	Max 3%
LOI	Max*	-	Max 6%		Max 0.5%	Max 6%
Na_2O_{eq}	-	-	-	-	Max*	-
* Depends on the type of SCM						

Table 2 – Overview of Physical Requirements in Different SCM Standard Specifications.

Physical Requirements						
Requirements	ASTM					AASHTO M 321 High Reactivity SCMs
	C618	C989	C1240	C1697	C1866	
	Ashes, Natural Pozzolan	Slag Cement	Silica Fume	Blended SCM	Ground-Glass Pozzolan	
Retained in No. 325 Sieve	Max 34%	Max 20%	Max 10% Max 5% variation from average	*Report only*	Max 5.0%	Max 10%
7-day Strength Activity Index	Min 75%	*Report only*	Min 105†	Min**	Min 75%	Accelerated, Min 85%
28-day Strength Activity Index	Min 75%	Min***	-	Min**	Min 85%	-
Water Requirement	Max*	-	-	*Report only*	*Report only*	-
Air Content	-	Max 12%	-	-	-	-
Specific Surface	-	-	Min 15 m^2/g	-	-	-
Autoclave Expansion	-	-	-	Max 0.8%	-	-
Relative Density	-	-	-	-	*Report only*	-
Uniformity: Density and Fineness	Max 5% variation from average	-	-	-	-	-
* Depends on the type of SCM	** Depends on blend type		***Depends on grade and samples		† Accelerated	

4.4. Specifications Shortcomings Related to Reactivity

In general, the reactivity of a SCM or ASCMs is inferred indirectly by the oxide composition, the SAI, and the fineness (determined by the amount retained on the No. 325 sieve), as presented earlier. Nonetheless, other means have been shown to be better indicators of the materials' reactivity.

4.4.1. Oxides Content

Historically, bulk chemical composition has been used to characterize SCMs. Oxide content, while it is a useful tool for quality control and production consistency overtime, has its limitations as a performance measure. However, SiO_2, Al_2O_3, Fe_2O_3 are used as quality check of fly ashes and natural pozzolans, silica fume, blended SCMs, ground glass pozzolan, and highly reactive pozzolans; CaO is used to provide an indication of hydraulic properties of fly ashes and blended SCMs, and the impact on the sulfate attack resistance and the alkali-silica reaction mitigation ability of fly ashes, natural pozzolans and ground glass pozzolan; SO_3 for potential setting, sulfate resistance and strength gain issues.

However, there is not always a definitive correlation between bulk chemical composition and performance. More important than the SiO_2, Al_2O_3, or Fe_2O_3 contents is the nature of these oxides, i.e., the amorphous content. For example, in fly ashes, the amorphous contents can vary significantly from 20 to 90%, affecting the pozzolanic behavior, and ultimately determining the strength and durability performance of the fly ash.[17], [18], [19], [20]. However, determining the amorphous content of an SCM requires more sophisticated techniques than determining chemical composition.

4.4.2. Strength Activity Index (SAI)

The SAI is an index between the strength of a mortar containing the SCM and of a mortar containing only portland cement. It is used as an indirect means to assess the reactivity of a particular SCM. Different SCM specifications have different versions of SAI but all of them have their own shortcomings.

Deficiencies of SAI according to ASTM C311/C311M-22[21]

- Cement Replacement Level: only 20% of the mass of the portland cement is replaced by the SCM. Since, this is a low level of replacement, in finely ground materials, the filler effect may control the strength, not necessarily the reactivity, allowing fillers to pass the SAI requirement.[22], [23]

  For example, a study using a modified C311/C311M [21](with constant water/ cementitious ratio) evaluated several potential natural pozzolans and an inert quartz. Due to the low replacement level, the inert quartz passed the SAI requirement of 75% of the control in all ages. The dilution effect this inert only had a significant impact on compressive strength at 90 days, however, not as significant to prevent passing the 75% of SAI [23].

- Cement Type: Type IL (ASTM C595/C595M-23[24]) cement is becoming more prevalent in the industry, however, C311/C311M only allows for the use of portland cement. Eventually, C331/C311M will allow the use of Type IL, however, it is not known yet, how its chemistry might affect the strength gain of a particular SCM, as compared with portland cement. Consequently, the SAI requirements of different specifications may require adjustments when Type IL cement is used.
- Replacement by Mass: cement replacement is made on the mass basis, however, because the specific gravity of the SCMs is, in general, significantly lower than that of the cement, for the same mass, the SCMs yield a higher volume, increasing the total volume of paste, and potentially affecting the water demand for a certain flow. Additionally, a higher volume of paste results in a reduction in the volume fraction of the water, which also plays a significant role in the porosity of the microstructure, consequently on the strength [25].

- **Constant flow:** the amount of water is adjusted so that the mortar has a flow within ± 5 of that of the control. As a result, the w/cm is variable. However, in practice, workability is controlled with the use of admixtures, not adjusting the water content. Some fly ashes improve workability and require less water than plain cement mixes, an improvement in strength may not be related to the reactivity of the fly ash, but to the lower w/cm.

  In a study, two different cements were tested with four SCMs. Depending on the SCM, the w/cm varied from 0.44 to 0.56, while the control had a w/c of 0.484 [25]. Additionally, the same cement-SCM combinations were tested with a constant w/cm and using 20% cement replacement, on a volume basis, instead of mass basis. It is well known that w/cm has a significant impact on the microstructure, and consequently, on the strength, thus it was not surprising to observe that in five out of eight cases, the mortars with variable w/cm and replacement by mass presented higher SAI than those volumetrically proportioned, with constant w/cm. Varying the w/cm masks the real effect of the SCM[25], [26], [27].

SAI for Fly Ashes, Natural Pozzolans (C618-23)[3] and Ground Glass Pozzolans (C1866/C1866M-22) [12]

- **SAI:** the strength activity index is determined according to ASTM C311/C311M-22, which presents its own weaknesses, as discussed previously.
- **Age of SAI:** C618-23 requires the strength of the mortar containing the SCM to be, at least, 75% of that of the control mortar at 7 and 28 days. Consequently, slowing reacting SCM may not be able to achieve this requirement[22], [23].
- **Strength Level:** It has been reported that the limit of 75% is too low and allows for fillers to pass the requirement. It has been suggested that a limit of 85% at 28 days would be more reliable to differentiate between reactive and nonreactive materials [25].

SAI for Slag Cements (C989/C989M-24)[5]

While in the SAI of slag cements, 50% of the mass of portland cement is replaced by the slag cement, which is much higher than what is required in ASTM C311/C311M, some of the same shortcomings in C311/C311M are still present, such as variable w/cm and portland cement replacement by mass. Additionally, not only does it require the use of ASTM C150[28] portland cement, but it requires a portland cement with specific range of total alkalis and minimum compressive strength at 28 days.

SAI for Silica Fume

Silica fume and high reactivity SCM SAI is obtained with a modified version of C311/C311M, where the water/cementitious ratio is kept constant, the flow is adjusted with a high-range water reducer admixture and the curing temperature between day 2 and day 7 is increased from 73 ± 4 °F to 149 ± 4 °F to accelerate the strength gain. Consequently, it presents the issues regarding the replacement by mass and the use of ASTM C150 portland cement.

SAI for Blended SCMs

It follows the SAI for their constituents, reflecting the same limitations.

4.4.3. Fineness

The fineness and the particle size distribution of an SCM influence the reactivity of the material, and the concrete fresh properties, strength development and other hardened properties. Even so, the only requirement related to fineness in all the ASTM and AASHTO SCM specifications, except for C1697-21[11], is the maximum amount retained on the No. 325 sieve. The amount retained on the No. 325 sieve just provides information on the amount of material bigger than approximately 45 μm.

Since the individual particle size of the SCMs, in general, is from 1 to 100 μm for fly ash, from 2 to 10 μm for metakaolin, from 1 to 60 μm for slag cement, from 0.1 to 0.3 μm for silica fume, less than 20 μm for pumice, and average of 5 μm for calcined shale, these particles are much smaller than the 45 μm of the No. 325 sieve[29], [30], [31], [32]. Consequently, such a requirement does not provide any meaningful information.

4.5. Other Methods to Assess Reactivity

4.5.1. Lime Strength Test

This test is based on a modification of CSA A3400-E1 and a modified version was developed at the University of New Brunswick. This test consists of measuring the compressive strength of a lime mortar cured at 100 °F for 6 days, after demolding. The reactivity threshold of this test method is 435 psi. Some studies showed poor correlation between 91-day compressive strength and the results of the lime strength test [33].

4.5.2. Chapelle test

A solution of SCM and $Ca(OH)_2$ is maintained at 210 °F for 16 h. The reactivity is shown by the calcium hydroxide consumed during this period. In a study by Seraj and Juenger it was observed that this methodology was not able to identify pozzolans with later reactivity [34].

4.5.3. Electrical Resistivity

Electrical resistivity is significantly affected by the densification of the microstructure provided by SCMs. For this reason, there has been growing interest in using bulk resistivity as a tool to assess reactivity of SCMs. ASTM is working on the development of a standard method for that purpose. However, if the same principles of mixture proportions and testing ages of ASTM C311/C311M are kept, the same shortcomings already discussed will be present.

Additionally, electrical resistivity is not only a function of the microstructure but is also significantly affected by the pore solution composition, which varies depending on the materials and proportions used in the mortar [35]. Thus, bulk resistivity of different mixtures should not be compared, making it difficult to establish an appropriate threshold between reactive-nonreactive material.

It should also be noted that ASTM C511 standard curing promotes leaching of alkalis, which in turn, notably affects the pore solution resistivity and the mortar resistivity.

In a study where the cubes were cured at 73 °F, bulk resistivity was able to differentiate inert from SCM at 28 days, with the exception of Class C fly ashes that showed low bulk resistivity values. In the same study when the cubes were cured at 120 °F, bulk resistivity better differentiate between reactive-nonreactive materials. However, this study presented data on a limited number of SCMs [36].

4.5.4. Isothermal Calorimetry and Bound Water

The reactivity quantification by isothermal calorimetry has been showing great potential to assess reactivity of different SCMs, including new SCMs and ASCMs with limited historical performance. A significant amount of research has been carried out since the 1950's using different techniques to assess the reactivity of certain SCMs [37], [38], [39], [40], [41]. Between 2010 and 2017, around 9,500 papers were published in international journals[42].

Most recently, a new approach, namely R3 – Rapid, Robust and Relevant, has been under consideration by RILEM, which has performed studies on the ruggedness and variability of the different approaches[43], [44]. Two approaches are used: a) isothermal calorimetry of paste at 100 °F for a week and b) conditioning of the same paste at 100 °F for a week and then performing bound water testing. This approach has been published in the U.S., in 2020, as ASTM C1897[45].

There are some drawbacks with C1897[45]. First, the paste can be mixed at 1,600 ± 50 rpm or according to C1738/C1738M[46], which reaches 10,000 rpms. The time of mixing also differs between the two methods. It is well known that mixing energy affects calorimetry results because higher shear rates promote better dispersion and deglomeration of cementitious materials. Additionally, for both methods, a blender is necessary, so the amount of materials needed to properly use a blender is several orders of magnitudes higher than the amount of materials necessary for certain isothermal calorimeters that allow only around 10 g of material per ampoule. This may lead users to mix the paste manually or with other types of mixers that do not apply the same shear rates, making it difficult to compare results from different laboratories.

Another possible source of problems with isothermal calorimetry is the use of plastic ampoules. When high testing temperatures are used and the test takes more than one or two days, plastic ampoules allow for a little evaporation through the walls of the ampoules. Since the isothermal calorimeter is very sensitive, this loss is captured as a decrease in the heat of hydration and in some cases, the material erroneously appears to be endothermic. This will be further discussed in Chapter 8.

Some studies [47], [48] have indicated that tests such C1897 may not properly characterize slow-reacting materials and proposed a modification to such tests. The modification consists of isothermal calorimetry at 120 °F, instead of 100 °F, for 10 days, instead of 7 days. The chemistry of the paste is also different, i.e., it doesn't contain sulfates and carbonates. This results in differences in pH.: 13.7 for the modified R3 and 12.9 for C1897. The liquid-power ratio is 0.9, instead of 1.2. Additionally, the bound water method does not easily allow the differentiation between pozzolanic and latent hydraulic materials, so instead, calcium hydroxide consumption is used.

Although, neither the C1897, also known as R3, or the Modified R3 classify the materials based on the test results, values to differentiate between inert, fly ashes and pozzolans, slags, silica fumes, and calcined clays have been proposed [49], [50].

4.6. Loss on Ignition (LOI) Specifications Shortcomings

The LOI requirement intends to limit possible air entrainment issues in fly ashes because carbon can adsorb air entraining admixtures (AEA). The extent of air entrainment adsorption issues depends not only on the amount of unburnt carbon but also on its porosity, pore size distribution, degree of activation and the nature of the original carbon. The degree of activation, on the other hand, is affected by burning conditions, the injection of powder activated carbon (PAC) into the flue gas for pollution control. It is important to highlight, that a negligible amount of PAC would result in a small LOI change, but it can significantly impact the fly ash adsorption capacity.[37], [51], [52]

That said, the LOI is unable to fully reflect the adsorption capacity of the fly ash because it is just a measure of the amount of unburnt carbon, and does not indicate the carbon's degree of activation, its porosity or pore size distribution.

Figure 2 shows the lack of correlation between the AEA demand and LOI. It is clear that even low LOI fly ashes may require high doses of AEA.

Additionally, Figure 2b shows that the AEA demand of a particular fly ash varies from admixture to admixture, as it is affected by the chemistry of a particular AEA.

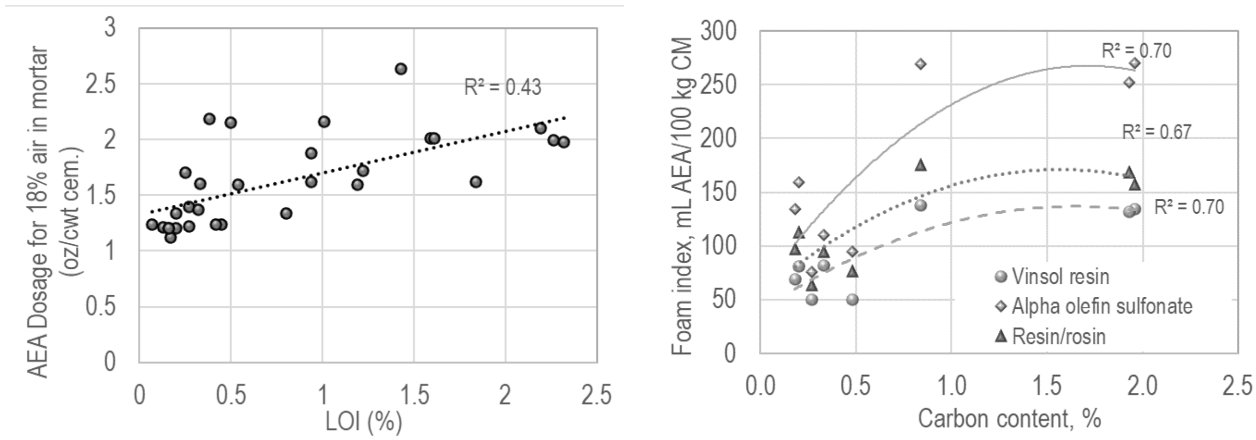


Figure 2 – Correlation between dosage of admixture and LOI. to achieve (a) 18% air entrainment in mortar[53], (b) stable foam[54].

4.7. Foam Index to Assess AEA Demand

Instead of relying on the LOI, Foam Index (FI) can be used to assess the AEA demand of a particular fly ash. Several versions of the foam index test exist [53], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], including a standardized one, ASTM C1827, "Standard Test Method for Determination of the Air-Entraining Admixture Demand of a Cementitious Mixture", first published in 2020. All the versions can be summarized as follows:

- A certain amount of cement, fly ash and water are mixed.
- Drops of a standard solution are added.
- The container is closed and shaken for a certain time.
- The sample is left to rest for a certain duration.
- If a stable foam does not cover the sample, steps 2 to 4 are repeated.

Differences in each of the steps described above, including standard solution concentration, type of air entraining admixture (AEA), shaking procedure, container geometry, cement chemistry, and resting time, just to name a few, may affect the results of different versions of the test. As such, their results should not be compared. Moreover, differences in procedures also affect the accuracy, the repeatability, and the reproducibility[53], [66].

Some of the testing variables that may affect the results and a summary of the different versions of the foam index are presented in Appendix C.

5.0 Proposed Materials for WHRP 0092-23-03

The approach for selecting the SCMs and ASCMs followed the decision process in Figure 3.

First an initial identification of sources satisfying the following basic requirements:

- Represent a wide range of properties and performance,
- Be readily or potentially available in the Wisconsin market, and
- Be available in large quantities or be easily scalable.

Since the project intended to establish appropriate tools to evaluate SCMs and ASCM, as well as to develop a database of their properties, sources with historical field performance in Wisconsin were also included.

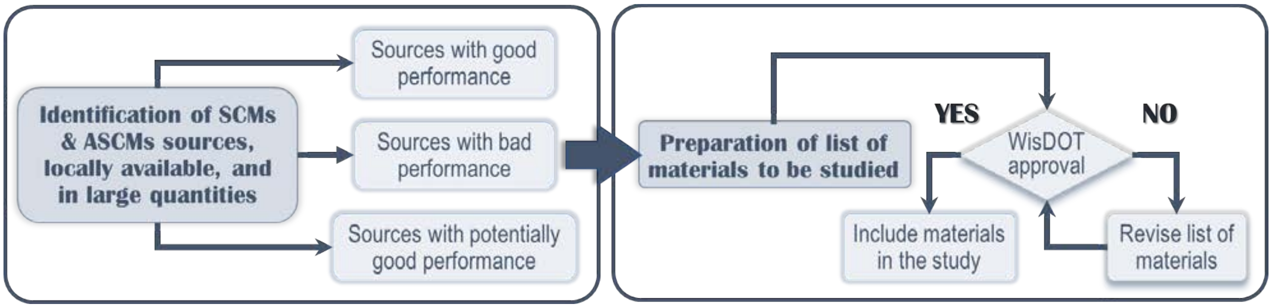


Figure 3 – Decision process for selection of SCMs and ASCMs to be used in the study.

5.1. Traditional Materials with Known Field Performance

The material selected for this study included traditional materials (Table 3) and new technologies (Section 5.2).

Table 3 – Traditional Materials Selected for the Study.

Material		Source
Fly Ash	Class C	Holcim from Elm Road Oak Creek, WI
		Holcim, from Weston Plant at Wausau, WI
	Class F	Eco Material Technologies, from Coal Creek at Underwood, ND
		Eco Material Technologies, from Prairie State Generating Station at Marissa, IL
Slag Cement		Votorantim from St. Mary's, MI

5.2. New Technologies with Little or No Performance History

5.2.1. Reclaimed Ash

This class C fly ash from Ottumwa, IA, was originally landfilled. It is processed by the National Minerals Corporation by drying and milling. A stockpile of approximately 300 kton is available for processing and use in concrete.

5.2.2. Opus SCM ™

Terra CO_2 produces an engineered cementitious material from readily available silicate rocks. The feedstock rock is subjected to a thermal process. The resultant material is vitrified and similar to a class F fly ash in terms of composition and morphology. Although it meets ASTM C618-23a chemical and physical requirements, it cannot be called fly ash, as it is not coal ash.

Terra's OPUS is an engineered cementitious material with a significantly lower carbon footprint than Portland cement. Only 0.283 tons of CO_2 is emitted for manufacturing a ton of OPUS Reagent compared to 0.922 tons of CO_2 per ton of Portland cement, driving a 70% reduction in CO_2.

The technology may be scalable and the SCM can be locally produced.

5.2.3. PozzoSlag ™

Eco Material Technologies produces PozzoSlag from class C fly ash. The proprietary process increases the reactive surface area and optimizes the particle size distribution. It has been approved by TxDOT for up to 50% replacement of cement under a Special Provision as a Modified Class Pozzolan. It is marketed to meet the chemical and physical requirements of ASTM C618-23a and of ASTM C989/C989M-22[5]. However, does not comply with the definition of slag cement, according to ASTM C125-21a[67]. It has also been called as a high reactivity SCM (AASHTO M 321-05(2021)[16]).

5.2.4. Micron^3 ™

Micron^3 is a by-product of the Coal Creek plant at Underwood, ND. Eco Material Technologies produces Micron^3, by separating the fines from ordinary fly ash. Consequently, it is an ultra-fine material, with a median particle size of 2 to 4 μm, and all the particles smaller than 10 μm. Its particle size is about 10 times smaller than a regular fly ash. Due to the particle size, it is mostly used in lieu of silica fume or metakaolin.

5.2.5. Liquid ASCM

The Liquid ASCM was composed of a combination of two admixtures: one to promote internal curing (E5 Cure™), and another one to promote densification of the matrix (E5 Liquid Fly™).

6.0 Testing Plan

This study is divided into two portions: materials evaluation and concrete performance. In both portions, 30% of the cement mass was replaced by the SCMs, except for the mixture containing Micron^3, where 10% % of the cement was replaced by Micron3 in conjunction with 20% of Marissa (Table 4). The cement used was a Type IL from Holcim Alpena. Liquid ASCM was only used in the concrete performance part of the study.

Table 4 – Cement Mass Replacement by Each SCMs and Dose of Liquid Fly Ash.

Material	ID Source	Cement Mass Replacement
Class C Fly Ash	Elm Road	30%
	Weston	30%
ASCM	Opus SCM TM	30%
	PozzoSlag TM	30%
Slag Cement	St. Mary's	30%
Class F Fly Ash	Coal Creek	30%
	Marissa	30%
	Micron^3 ™ + Marissa	10% Micron^3 and 20% Marissa fly ash
Liquid ASCM	E5 Cure™ and E5 Liquid Fly™	4 oz/cwt and 8 oz/cwt

6.1. Materials Characterization

The materials' evaluation involved a comprehensive assessment of the SCMs and ASCMs, including chemical analysis, physical testing, and reactivity characterization (Figure 4).

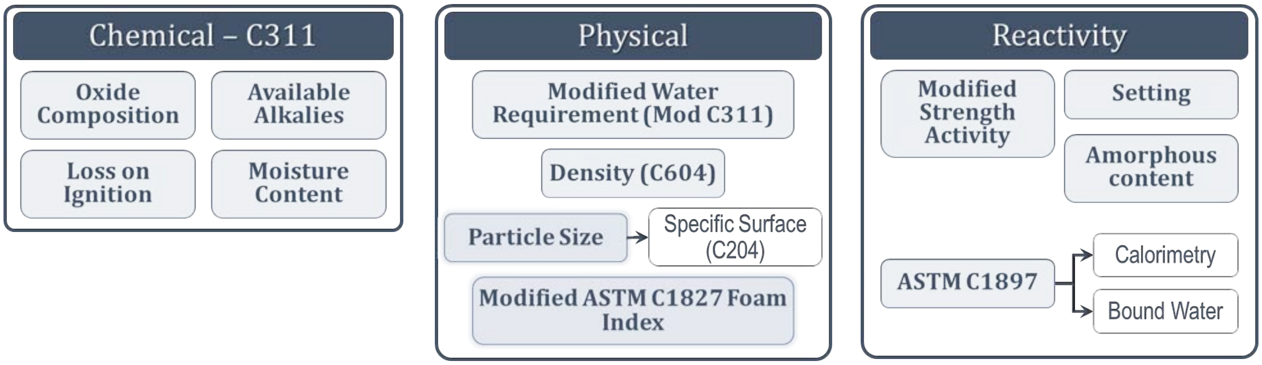


Figure 4 – Characterization of SCMs and ASCMs.

6.1.1. Chemical Analysis

Chemical analysis was performed according to ASTM C311/C311M-24[21]. Physical testing included a modification of water requirement (modified ASTM C311/C311M-24), described below, density according to ASTM C604-18 (2023)[68], specific surface according to ASTM C204-24[69], and a modified version of ASTM C1827-20 foam index [61], also described below. Reactivity was investigated through a modified version of the ASTM C311/C311M-24[21] strength activity index, described below, setting time according to a modification of ASTM C191-21[70], and ASTM C1897-20[45] described below.

6.1.2. Amorphous Content

Amorphous content was obtained by X-ray diffraction (XRD), which was performed on a Bruker D2 Phaser equipped with a Copper tube radiation source with a slit opening of 1 mm. Measurements were made with an operating voltage of 30 kV and amperage of 10 mA. Diffraction counts were gathered with a Lynxeye detector at an angle of 5 degrees. The sample was screened over a #200 sieve and passing material was then scanned from approximately 5 degrees to 65 degrees 2 theta. An internal reference standard ('spike') of aluminum oxide was added to the sample, and then it was scanned in a similar manner as above to determine amorphous content. The data collected was compared to the PDF-4 International Center for Diffraction Data database for phase identification.

6.1.3. Modified Strength Activity (Mod SAI)

So as to overcome some of the ASTM C311/C311M-22 deficiencies, highlighted in the Literature Review (Section 4.4.2), a modified version was performed in this study:

- A Type IL cement was used.
- To take into account the different specific gravities of the SCMs, the sand volume was adjusted to keep a fixed volume of mortar.
- The water to cementitious ratio (w/cm) was kept constant.
- In all mixtures, the cement replacement was increased to 30% by mass, instead of 20%.
- The flow was not maintained within ± 5 from the flow control plain mortar (Table 5).

The test methodology is presented in Appendix D.

6.1.4. Modified Setting Time

The modified setting time was based on ASTM C191-21[70] but had replacement of 30% and a fixed w/cm.

Table 5 – Density of Cement and SCMs, and Mortars Mixture Proportions for the Modified Strength Activity Index and Setting Times.

Material	Density, g/cm^3	Alpena 1L Cement, g	SCM, g	Graded Standard Sand, g	Water, g	Flow
Control	3.12	740	0	2035.0	362.6	93
Elm Road	2.58	518	222	1993.0	362.6	127
Weston	2.66	518	222	1998.1	362.6	127
Reclaimed Ash	2.55	518	222	1989.5	362.6	112
Coal Creek	2.46	518	222	1989.5	362.6	136
Marissa	2.34	518	222	1970.4	362.6	135
OPUS	2.50	518	222	1989.5	362.6	128
PozzoSlag	2.51	518	222	1997.1	362.6	148
Slag	2.87	518	222	2015.4	362.6	101
10% Micron^3+ 20% Marissa	N/A	518	74/148[2]	1979.4	362.6	140

[1]Flow was determined according to ASTM C1437-20[71], 25 drops.
[2]Indicates 74 g of Micron^3 and 148 g of Marissa

6.1.5. Modified Water Requirement (Mod C311)

Because the modified SAI water requirement was not necessary, water requirement was only performed to evaluate the effect of each SCM on the workability of the mortar. However, a modified version of the water requirement in C311/C311M-22 was carried out. The modified water requirement was based on ASTM C311/C311M-22, with two exceptions: a) due to the various specific gravities of the SCMs, the volume of cement plus SCM plus graded standard sand was kept constant, and the cement replacement level was 30% by mass, instead of 20%. The water was then adjusted to maintain a flow of ± 5 the flow of the control mixture. Table 6 shows that the w/cm varies from 0.40 to 0.49. It is important to highlight that only the slag had a slightly higher water demand than the control. All other materials showed lower water demand.

6.1.6. Modified Foam Index (Mod C1827)

As previously explained in the literature review, section 4.6, LOI is not always the best indicator of the capacity of an SCM to adsorb AEA and affect air entrainment. With the intention to gain a better understanding of the interaction between SCM and AEA, the foam index test was performed according to a modification to ASTM C1827-20[61], proposed by Ley, with the exception that mechanical means were used to prepare the samples. A detailed procedure is presented in Appendix C.

6.1.7. Reactivity of SCMs and ASCMs by ASTM C1897

Reactivity was evaluated according to ASTM C1897-20[45], using both the calorimetry and the bound water methods. C1897-20[45] was performed in all SCMs and ASCMs with the exception of the Liquid ASCM, since it is an admixture. Two replicates per material, from the same batch, were tested. Different batches of materials were prepared to evaluate the within laboratory variability.

Table 6 – Mortars Mixture Proportions for Water Requirement and Flow.

Material	Alpena 1L Cement, g	SCM, g	Graded Standard Sand, g	Water, g	w/cm	% Water of Control	Flow
Control	500	0	1375.0	242	0.484	100%	111
Elm Road	350	150	1346.6	215	0.430	89%	108
Weston	350	150	1350.0	221	0.442	91%	115
Reclaimed Ash	350	150	1344.3	239	0.478	99%	110
Coal Creek	350	150	1344.3	214	0.428	88%	112
Marissa	350	150	1331.3	215	0.430	89%	115
OPUS	350	150	1344.3	214	0.428	88%	109
PozzoSlag	350	150	1349.4	200	0.400	83%	111
Slag	350	150	1361.8	245	0.490	101%	110
10% Micron3+ 20% Narissa	350	50/100[2]	1337.4	215	0.430	89%	111

[1]Flow was determined according to ASTM C1437-20, 25 drops.
[2]Indicates 50 g of Micron3 and 100 g of Marissa

A Calmetrix calorimeter was used for isothermal calorimetry measurements. Slurries were mixed according to ASTM C1738/C1738M-19[46], because it promotes the best dispersion of the materials, helping to evaluate the reactivity. The mixing procedure significantly affects the heat released and the evaluation of the reactivity of the SCMs. The materials were mixed at 39 ± 1 °C, so once the samples were inserted in the calorimeter, they would be at about the same temperature as the calorimeter itself (40 °C), facilitating the temperature stabilization.

Another important step was the proper sealing of the samples, so no mass would be lost to evaporation during testing. Samples were weighed into polypropylene bags, tied and placed into a Mylar bag. Then, the Mylar bag was heat sealed and placed into a 4-ounce HDPE container, which was lidded and placed into the calorimeter chamber. An overview of the procedure is shown in Figure 5. The mass of materials mixed in each batch is shown in Table 7.

Table 7 – ASTM C1897-20 [45] Samples Mixture Proportions.

	Material	Mass
Calcium powder	$Ca(OH)_2$	168 ± 0.01 g
	$CaCO_3$	28 ± 0.01 g
	SCM	56 ± 0.01 g
Potassium Solution	Potassium Hydroxide	1.18 ± 0.01 g
	Potassium Sulfate	5.91 ± 0.01 g
	Reagent water	295 ± 0.01 g

For the bound water content method, instead of remixing the paste and storing it at 40 °C, since the calorimetry samples were also tested at this temperature, once the calorimetry test was complete, the same samples were used for bound water content determination (Figure 5).

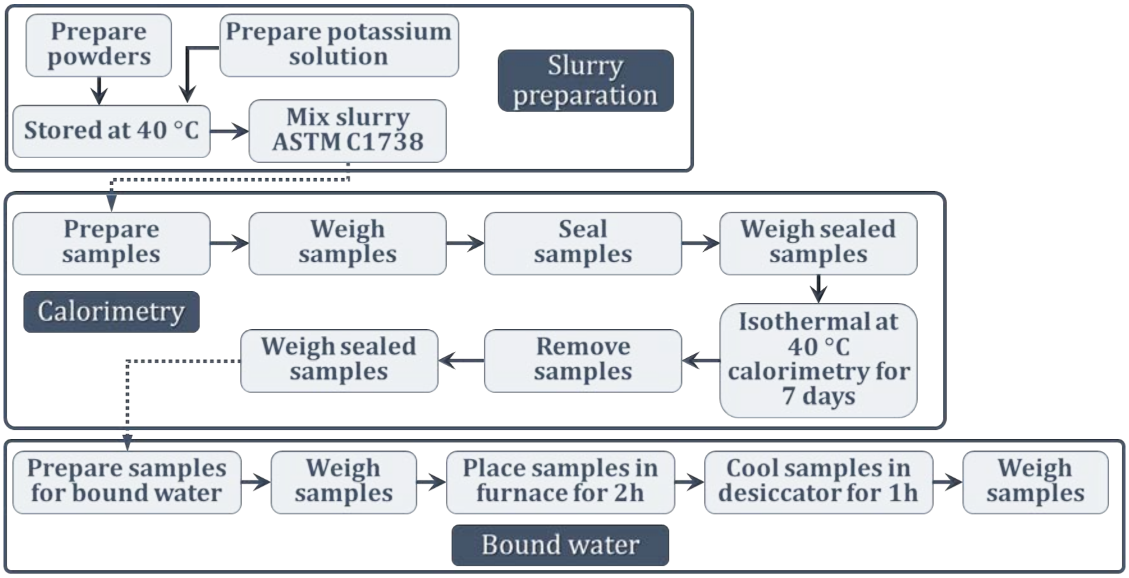


Figure 5 – ASTM C1897-20[45] reactivity testing overview.

There was an attempt to perform the modified R3, as described by Suraneni and Weiss [71]. But, some of the materials could not be properly mixed, due to the liquid/solid ratio specified as 0.9. So, the modified R3 was not performed.

6.2. Concrete Performance

6.2.1. Concrete Mixture Proportions

Concrete was proportioned according to ACI PRC 211 [72]. The coarse aggregate was a dolomitic limestone from Lannon Stone. Two coarse aggregate sizes were blended in proportions to fit the tarantula curve (Figure 6). The final blend specific gravity was 2.77 and the absorption was 0.94. The fine aggregate used was a natural sand, with specific gravity of 2.66, fineness modulus of 2.64, and absorption of 0.9. The tarantula curve is shown in Figure 6. Cement was replaced by SCMs applying the same replacement rates used in section 6.1. Additionally, a concrete mixture was prepared using the Liquid ASCM. The mixture proportions are shown in Table 8.

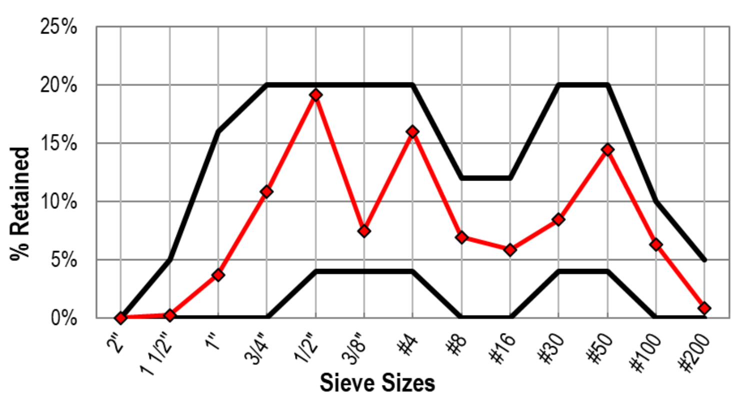


Figure 6 – Tarantula curve.

Due to the large volume of concrete needed to perform all the concrete tests, two 4.75 ft^3 batches of concrete for each SCM evaluated were prepared according to ASTM C192/C192M-19[73]. The mixing procedure for the Liquid ASCM was modified from C192/C192M according to the manufacturer's recommendation, as follows: Mixture was prepared according to C192/C192M-19, then the admixture for the densification of the matrix was added with a syringe while the drum was rotating. Mixing continued for 2 minutes. Afterwards, the admixture for internal curing was added with a syringe while the drum was still rotating and mixing continued for 2 min. Specimens were made and cured according to AASHTO R 39M/R 39-23[74].

6.2.2. Concrete Testing

Concrete fresh properties were obtained as follows:

AASHTO T 119M/T 119-23 [75](slump) and AASHTO T 396-22 (Box Test)[76], as a workability measure, unit weight according to AASHTO T 121M/T 121-23[77], air according to AASHTO T 395-22[78], and setting according to AASHTO T 197M/T 197-23[79].

The tests performed in the hardened concrete are shown in Table 9. In addition, calcium oxychloride formation was quantified according to AASHTO T 365-20[80].

7.0 Test Results

For each test performed, data were analyzed comparing the results among the mixtures and, when possible, comparing with benchmark values from the industry, specifications or test methods. When sufficient data were available, statistical analysis was carried out. A one factor Analysis of Variance (ANOVA) test followed by a Tukey Honestly Significant Difference (HSD) with a 95% confidence was performed.

Analysis of variance (ANOVA) is a statistical technique used to check if the means of two or more groups are significantly different from each other. This is done by examining the amount of variation within each sample, relative to the amount of variation between the samples. In an ANOVA test, first the variance of each group is calculated and then, the variance of each group is compared to the overall variance of the group means. Generally speaking, when a large difference in means is combined with small variances within the groups, there is a statistically significant difference among the groups. On the other hand, when a small difference in means is combined with large variances within the groups, there is no statistically significant difference among the groups.

When an ANOVA gives a significant result, this indicates that at least one group differs from the other groups. However, it will not tell where exactly those differences lie. The Tukey HSD test, which is a post-hoc test based on the studentized range distribution, will show which specific groups' means (compared by pairs) are statistically different [81].

All the statistical analysis can be found in Appendix F.

Table 8 - Concrete Mixture Proportions Used in this Study.

Mix	Type IL Cement, lb/yd^3	SCM, lb/yd^3	#4 aggregate, lb/yd^3	#57 aggregate, lb/yd^3	Sand, lb/yd^3	Water, lb/yd^3	AEA, Polychem VR, oz/cwt		Type A Polychem Paver Plus, oz/cwt		Liquid ASCM for	
											Internal curing, oz/cwt	Densification, oz/cwt
							Batch 1	Batch 2	Batch 1	Batch 2	Batches 1 & 2	
Control	530	0	266	1634	1343	223	1.1	1.1	4.5	4.5	-	-
Elm Road	420	180	266	1634	1180	252	1.1	1.0	4.0	4.5	-	-
Weston	371	159	266	1634	1320	223	1.0	1.0	4.0	4.0	-	-
Reclaimed Ash	371	159	266	1634		223	1.1	1.0	3.6	3.3	-	-
Coal Creek	420	180	266	1634	1171	252	1.0	1.1	3.4	4.0	-	-
Marissa	420	180	266	1634	1161	252	1.0	1.2	4.0	4.1	-	-
OPUS	371	159	266	1634	1311	223	1.0	1.0	4.0	4.1	-	-
PozzoSlag	371	159	266	1634	1310	223	1.0	1.0	3.9	3.9	-	-
Slag	371	159	266	1634	1332	223	1.2	1.2	4.0	4.0	-	-
Micron^3 + Marissa	371	53/106	266	1634	1303	223	1.0	1.0	4.0	4.0	-	-
Liquid Fly Ash	530	0	266	1634	1343	223	1.0	0.8	4.0	4.0	4.0	8.0

Table 9 – Hardened Properties, Test Methods, Specimens and Testing Ages.

Material	Specimens per age	Specimen size, in.	Testing age, days
Compressive strength, AASHTO T 22M/T 22-22[82]	2	6 by 12	3, 7, 28, 91
Flexural strength, AASHTO T 97M/T 97-23[83]	2	6 by 6 by 20	3, 7, 28
Shrinkage, modified ASTM C157/C157M-17[84]	3	4 by 4 by 11.25	Drying from time of demolding until 28 days.
Freeze-thaw resistance, AASHTO T 161-22, procedure A[85]	3	3 by 4 by 16	N/A
Surface resistivity, AASHTO T 358-22[86]	2	6 by 12	3, 28, 91, 180

7.1. Materials Characterization Test Results

In this chapter, the test results of materials characterization will be summarized. For complete access to all test results refer to Appendix E.

7.1.1. Oxide Composition

Table 10 shows the oxide composition of the SCMs in the study and the standard specification requirements. It can be observed that Elm Road, Weston, and Reclaimed Ash materials comply with Class C fly ash chemical requirements, Coal Creek, Marissa, Opus and Micron3 materials comply with Class F fly ash chemical requirements, and St. Mary's Slag complies with the slag cement chemical requirements. PozzoSlag is marketed as meeting chemical requirements of ASTM C618-23a for Class C and of ASTM C989/C989M-22. As seen is Table 10, it meets only the requirements for Class C Fly ash. Figure 7 shows the chemical composition of the materials used situated in the major SCM groups.

Table 10 – Oxide Composition.

Chemical Composition, % mass	**Class C Fly Ashes**					**Slag**	
	Elm Road	Weston	Reclaimed Ash	PozzoSlag	ASTM C618 requirements	St. Mary's Slag	ASTM C989 Requirements
Silicon as (SiO_2)	39.46	38.14	33.83	44.31	-	33.25	-
Aluminum as (Al_2O_3)	19.69	19.43	19.27	19.58	-	13.53	-
Iron as (Fe_2O_3)	9.54	6.23	5.52	7.04	-	0.82	-
SUM (SiO_2+ Al_2O_3+ Fe_2O_3)	68.69	63.80	58.62	70.93	≥ 50.0	-	-
Sulfur as (SO_3)	2.16	1.33	1.56	2.24	≤ 5.0	1.80	-
Calcium as (CaO)	18.21	23.65	22.40	20.42	>18.0	42.90	-
Sulfide Sulfur (S)	-	-	-		-	0.47	≥2.5
Magnesium as (MgO)	4.20	5.74	4.10	4.35	-	6.12	-
Sodium as (Na_2O)	1.37	1.94	2.62	1.11	-	0.22	-
Potassium as (K_2O)	0.89	0.57	0.48	0.70	-	0.41	-
Total Alkali as (Na_2O_e)	1.96	2.32	2.94	1.57	-	-	-
Moisture Content:	0.06	0.11	2.53	0.38	≤ 3.0	-	-
Loss on Ignition (LOI)	0.65	0.37	5.38	0.53	≤ 6.0	0.62	-

Table 10 – Oxide Composition (Continued).

Chemical Composition, % mass	Marketed as Class F Fly Ash				
	Coal Creek	Marissa	OPUS	Micron[3]	ASTM C618 Requirements
Silicon as (SiO_2)	50.96	56.21	61.88	49.93	-
Aluminum as (Al_2O_3)	15.69	18.69	14.78	15.73	-
Iron as (Fe_2O_3)	5.74	9.72	8.48	5.30	-
SUM (SiO_2+ Al_2O_3+ Fe_2O_3)	72.39	84.62	85.14	70.96	≥ 50.0
Sulfur as (SO_3)	0.78	0.91	0.12	1.14	≤ 5.0
Calcium as (CaO)	14.64	6.23	5.24	13.62	≤ 18.0
Magnesium as (MgO)	4.20	1.49	3.15	4.09	-
Sodium as (Na_2O)	4.03	1.29	2.66	4.18	-
Potassium as (K_2O)	2.18	2.67	3.21	2.72	-
Total Alkali as (Na_2O_e)	5.46	3.05	4.77	5.97	-
Moisture Content:	0.09	0.04	0.09	-	≤ 3.0
Loss on Ignition (LOI)	0.27	0.70	0.07	0.41	≤ 6.0
Insoluble Residue (IR)	41.11	74.01	66.22	26.61	-

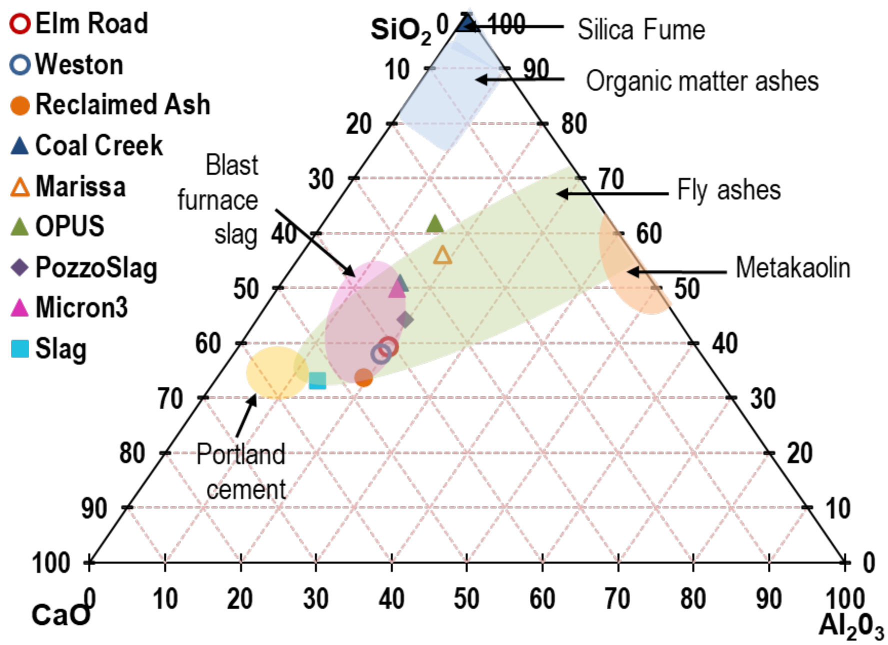


Figure 7 – Ternary CaO-SiO_2-Al_2O_3 diagram (wt% based) situating the chemical constitution of the major SCM groups (modified after [87]).

7.1.2. Density

The densities varied from 2.34 g/cm³ to 2.87 g/cm³. When cement replacement is made by mass, the difference between the cement density and the SCMs results in a larger volume of SCM than that of cement. The range of densities of materials that are marketed as fly ashes was from 2.34 g/cm³ to 2.66 g/cm³, and with an average of 2.52 g/cm³ (Figure 8).

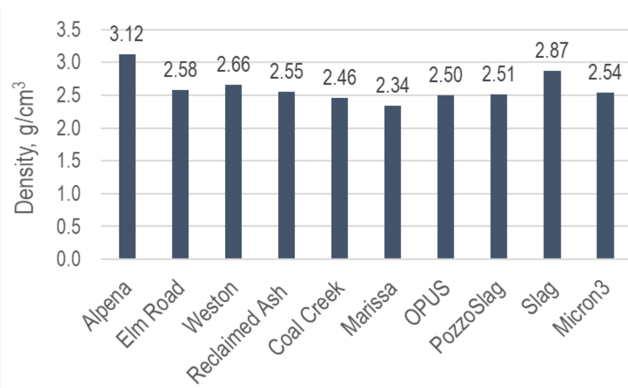


Figure 8 – Densities according to ASTM C604[68].

7.1.3. Water requirements

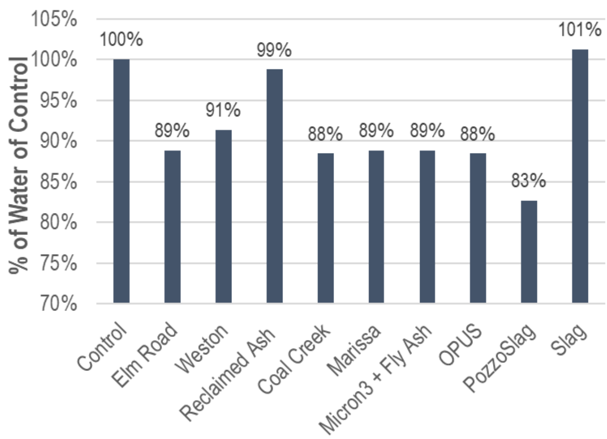


Figure 9 – Water requirement to achieve ± 5% of the control flow, according to modified ASTM C311/C311M-24[21].

Figure 9 shows the water requirement for the materials in this study. Note that in ASTM C311/C311M-24[21], the cement replacement is 20%, while in this study it was 30%. There was no difference between Reclaimed Ash, Slag and the control, while all the remaining materials provided a significant improvement of the workability, indicated by the lower water requirement. PozzoSlag provided the largest decrease in water requirement. The lower water requirement indicates that a lower w/cm could be used or possibly a lower dosage of water reducing admixture in concrete mixtures.

All materials pass the respective standards for water requirements.

7.1.4. Interaction Between SCMs and AE

Modified Foam Index

The results for the modified foam index are shown in Table 11. Three different operators performed the tests (foam index 1 through 3). Only Coal Creek has a foam index with a coefficient of variation (COV) higher than 20%, all the other materials had an average COV of 9%. It was expected that the relative foam index (foam index of material normalized by the foam index of the control mixture) would be equal or above 1, i.e., the SCMs would have no impact on AEA demand or would adsorb the AEA and increase its demand. However, only Weston and Marissa showed no effect on AEA demand, Elm Road slightly increased the AEA demand and PozzoSlag significantly increased the AEA demand. Surprisingly, all other materials presented a relative foam index significantly lower than 1, which would suggest a positive effect of the SCM. This effect has not been documented in the literature, but it may have been due to the use of Type IL cement which contains fine limestone and a high Blaine. The cement itself could have adsorbed AEA, especially the limestone particles. Once the cement was replaced by the SCMs, the AEA demand by the cement decreased[88], [89].

Table 11 – Modified Foam Index Test Results

	Foam Index 1, mL/g	Foam Index 2, mL/g	Foam Index 3, mL/g	Average Foam Index, mL/g	Stdev Foam Index, mL/g	COV, %	Relative foam index, %
Control	0.127	0.159	0.148	0.145	0.016	11%	
Elm Road	0.158	0.159	0.201	0.173	0.025	14%	119%
Weston	0.148	0.116	0.148	0.137	0.018	13%	95%
Reclaimed Ash	0.095	0.106	0.074	0.092	0.016	18%	63%
Coal Creek	0.063	0.106	0.106	0.091	0.024	27%	63%
Marissa	0.137	0.148	0.148	0.144	0.006	4%	100%
OPUS	0.053	0.053	0.053	0.053	0.000	0%	37%
PozzoSlag	0.201	0.223	0.243	0.222	0.021	9%	153%
Micron^3 +Marissa	0.111	0.111	0.111	0.111	0.000	0%	77%

7.1.5. Properties Relating to Reactivity

Particle Size

The specific surface results are shown in Figure 10. Elm Road and PozzoSlag showed specific surfaces similar to cement. Weston, Reclaimed Ash, and Slag showed similar specific surfaces. Opus showed a much higher specific surface and Micron^3, as expected, showed the highest of all, surpassing 600 m^2/kg.

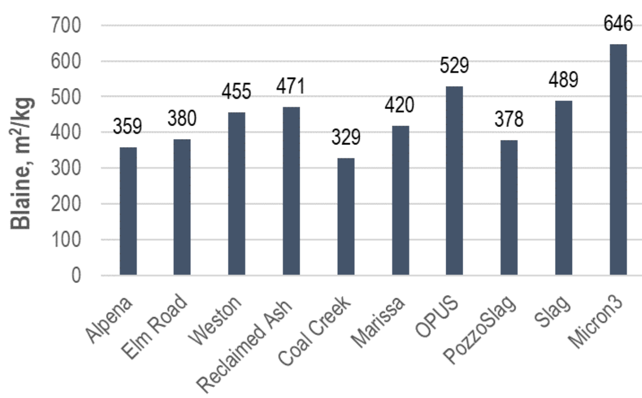


Figure 10 – Particle size (Blaine) determined according to ASTM C204[69].

Setting Time

Setting times varied widely when the same water content was used for all mixtures (Table 12 and Figure 11). The lowest initial and final setting times was for the slag cement (335 min and 490, respectively), which was close to what the control setting times were. The reclaimed ash was not significantly delayed either, however the other materials had a substantial impact on the setting times. This does not mean that in the field, such delays would occur, because in the field, the amount of water and the presence of water reducers would be adjusted for the desired workability and would definitely be much lower than the one in this study (0.49). This setting delay was probably due to the dilution effect.

Among the class C fly ashes, the setting times of the mixture containing the reclaimed ash was the least affected, while Elm Road and Weston presented similar behavior, with significant delays (Figure 11).

Table 12 – Setting Time.

	Initial set, min	Final set, min	Difference from control initial set, min	Difference from control final set, min	% of control initial set	% of control final set
Control	300	480				
Elm Road	640	810	340	330	213%	169%
Weston	630	735	330	255	210%	153%
Reclaimed Ash	380	535	80	55	127%	111%
Coal Creek	545	740	245	260	182%	154%
Marissa	460	685	160	205	153%	143%
OPUS	465	610	165	130	155%	127%
PozzoSlag	595	795	295	315	198%	166%
Slag	335	490	35	10	112%	102%
$Micron^3$ + Marissa	520	675	220	195	173%	141%
Minimum	335	490				
Maximum	640	810				

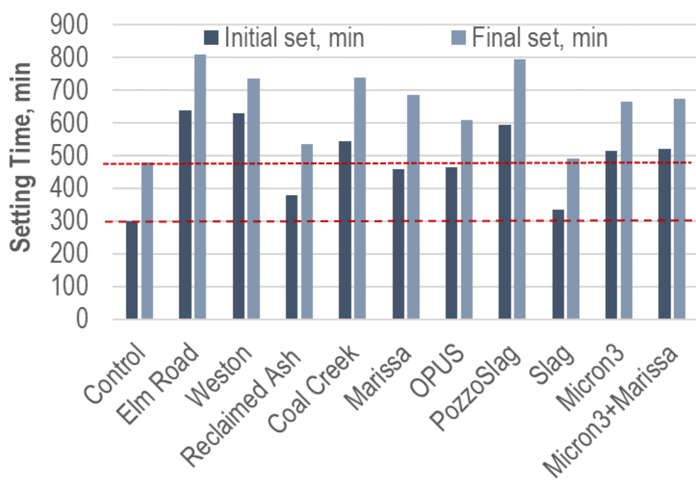


Figure 11 – Setting time. Dashed lines show initial and final setting of control mixture

Among the remaining materials, the mixtures containing Marissa and Opus presented similar behavior. Marissa didn't seem to have an effect on the mixture with Micron3, since the setting time behavior of both mixtures $Micron^3$ and $Micron^3$ + Marissa was almost identical. The most extreme behavior was shown by PozzoSlag (Figure 11).

It appears that there is a relationship between the oxides and setting time. Materials with high SiO_2 (above 50%) and a high sum of SiO_2+ Al_2O_3+ Fe_2O_3 (above 70%) led to shorter setting times, with the exception of Coal Creek, whose low fineness may have impacted its setting time. There was no correlation between SO_3 and setting time but a trend was observed, i.e, for each fly ash group, the lower the SO_3, the lower the setting delay.

Modified Strength Activity Index

As previously mentioned, the mortars for the modified strength activity index were prepared with a fixed w/c of 0.49 and with 30 % of cement replacement on a mass basis (Table 13). Figure 12 presents the modified SAI. Note that SAI for ages beyond 28 days are based on the 28-day control compressive strength. At 28 days, Elm Road, Weston, PozzoSlag and Slag either reached close to 100% SAI or surpassed it. At 56 days, only reclaimed ash, Coal Creek and Marissa, did not reach 100% SAI. However, they either reached it or surpassed it by 90 days.

Table 13 – Mixture proportions and flow of mortar mixtures.

Material	Alpena 1L cement, g	SCM, g	sand, g	water, g	flow, %
Control	740	0	2035	362.6	93
Elm Road	518	222	1993	362.6	127
Weston	518	222	1998.1	362.6	127
Reclaimed Ash	518	222	1989.5	362.6	112
Coal Creek	518	222	1989.5	362.6	136
Marissa	518	222	1970.4	362.6	135
OPUS	518	222	1989.5	362.6	128
PozzoSlag	518	222	1997.1	362.6	148
Slag	518	222	2015.4	362.6	101
Micron3 + Fly Ash	592	74/148	1979.4	363.6	140

At 7 days, all mixtures presented lower compressive strength than the control. However, at 28 days some of the materials started catching up with the control: Elm Road, PozzoSlag and Slag were statistically similar to the control, while Weston and Micron^3 surpassed the control. The addition of Micron3, improved the compressive strength development and final strength of Marissa.

The ratio between the compressive strength at two different ages is shown in Table 14. Note that for the compressive strength data for the Control mixture is only available until 28 days. Table 14 shows that for Elm Road, Weston, Reclaimed Ash and PozzoSlag there is not a significant increase in strength from 28 to 56 days. On the other hand, the other materials show a higher increase in strength in the same period. From 28 to 90 days, these materials had an increase in strength ranging from 22% to 36%. It is probably due to the pozzolanic reactions and shows that 28 days is not a good age to determine the modified SAI. Some materials, such as Marissa, may need 90 days to show the true potential of the material in terms of strength.

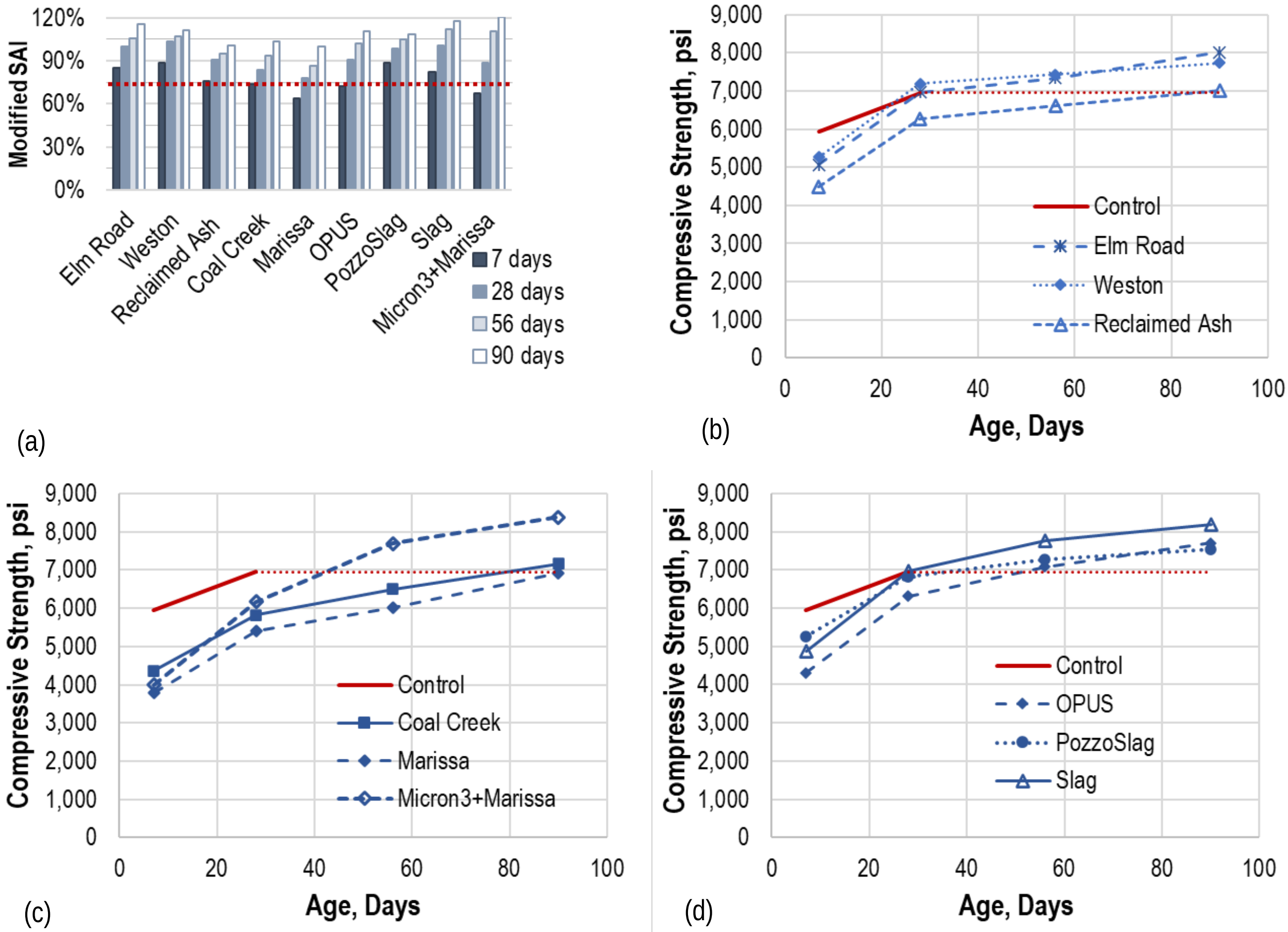


Figure 12 –Modified strength activity index (SAI). 56 and 90 days were calculated based on the 28-day strength of the control. (a) Red dashed line (75%) corresponds to specification requirement at 28 days, (b), (c), and (d) Red dashed line represents the 28-day strength of the control mixture.

Table 14 – Ratio between mortar strength at two different ages.

Age	28/7days	56/28 days	90/28 days
Control	1.17		
Elm Road	1.38	1.05	1.15
Weston	1.36	1.03	1.08
Reclaimed Ash	1.40	1.05	1.11
Coal Creek	1.33	1.12	1.23
Marissa	1.43	1.11	1.28
Micron3+ Marissa	1.54	1.25	1.36
OPUS	1.46	1.12	1.22
PozzoSlag	1.30	1.07	1.11
Slag	1.43	1.11	1.18

Crystallinity

Table 15 shows the amorphous content and the major and minor phases of the SCMs. The diffractograms of all the materials, with exception of slag, presented quartz as the major mineral phase. The amorphous contents ranged from 48.3% to 96.3%. Of the tested materials, Weston presented the lowest amorphous content, while Reclaimed Ash, Coal Creek, Marissa, Slag and Micron3 all presented amorphous contents above 90%. Appendix E presents all XRD diffractograms of the SCMs in this study.

Table 15 – Mineral composition determined by XRD.

	Amorphous Content	Major Phases	Minor Phases	Other Phases
Elm Road	86.1	Quartz	Anhydrite	Hematite, Periclase
Weston	48.3	Quartz	Periclase	Lime, Hematite
Reclaimed Ash	95.6	Quartz	Calcite	Gypsum
Coal Creek	94.9	Quartz	-	-
Marissa	96.3	Quartz	Magnetite	Portlandite, Hematite
OPUS	79.7	Quartz	Albite	
PozzoSlag	89.6	Quartz	Gypsum	Mullite, Anhydrite, Periclase, lime
Slag	93.0	-	-	-
Micron3	90.9	Quartz	Anhydrite	-

ASTM C1897

Figure 13 shows the results of the reactivity tests. Tests were performed in duplicates and repeated once or twice more, depending on the material. A total of 38 cumulative heat released and 38 bound water test results were obtained. Each point in Figure 13 c and d represents an average of two replicates. All tested materials surpassed the 90% confidence threshold for reactive materials [50].

The correlation between the two procedures is relatively good, when two of the points are excluded. These points were excluded based on inconsistent replicate data of bound water (Figure 13c) that indicated issues with the samples. As expected, class C fly ash showed higher reactivity than class F fly ash, due to its hydraulic properties, and slag showed the highest reactivity of all materials. Non-conventional materials reactivity spread from class F to class C ranges.

In terms of testing methodology, the calorimetry and the bound water methods were compared. In both methods, it is extremely important to make sure that samples are perfectly sealed, so there is no minor moisture change during the 7-day testing period at 40 ± 2 °C. The best option is to use glass containers. This is possible with the bound water method, since there is no restriction regarding containers size, but not always possible with calorimetry, where a specific calorimeter brand might not provide glass vials that fit the calorimeter cells. This was the case of the calorimeter used in this study, Calmetrix. Since there was no glass vial that would fit the Calmetrix cells, after consulting the manufacturer, a sealing method was developed, as mentioned in section 6.1.5. This sealing method was shown to avoid moisture exchange between the cell and the vials during testing. However, it is cumbersome and time consuming.

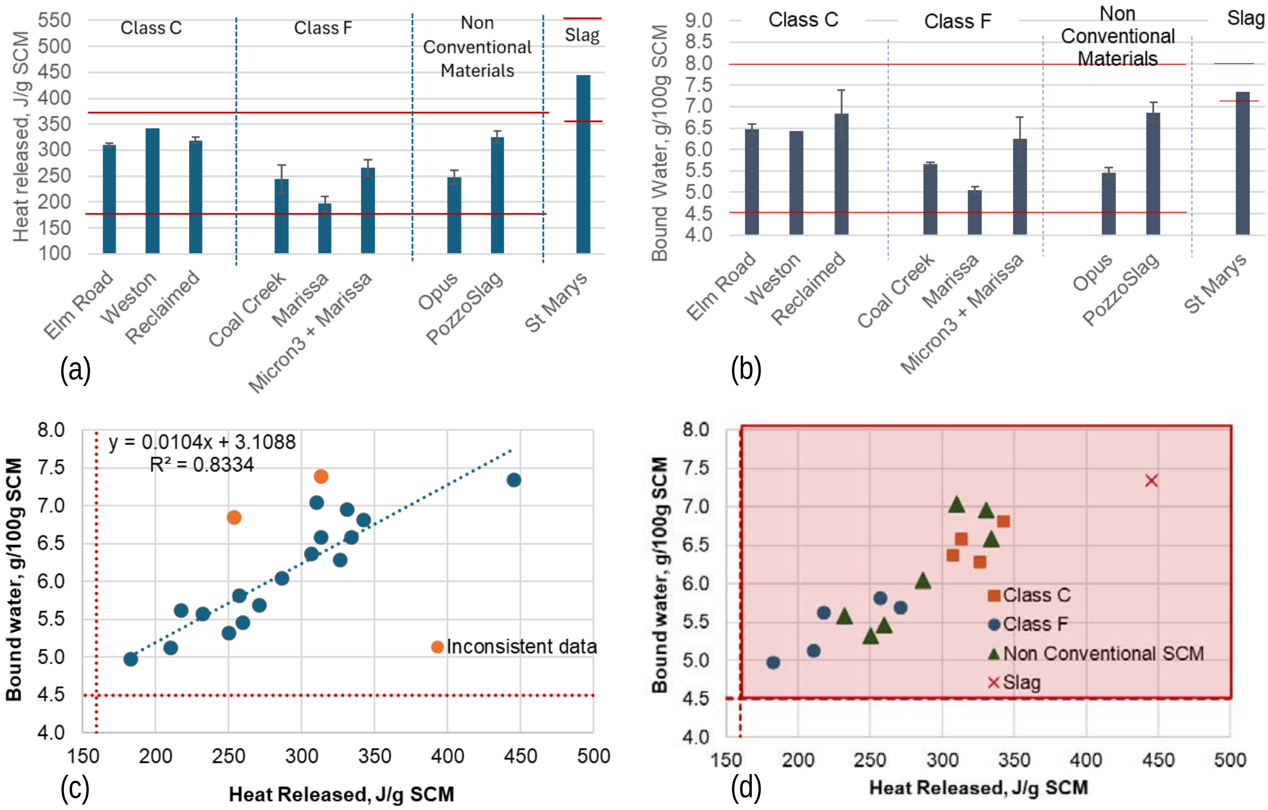


Figure 13 – ASTM C1897 test results. (a) Cumulative heat released at 7 days, (b) Bound water at 7 days, (c) Correlation between cumulative heat released and bound water at 7 days, (d) Cumulative heat released versus bound water for each SCM group. Red lines in a and b represent the range of expected cumulative heat released and bound water for reactive materials [50]. Dashed lines in c and d indicate reactive thresholds for 90% confidence, as per Londono-Zuluaga et al.[50].

Based on the tests performed, it was observed that the variability between two replicates from the same batch was 4.2% for bound water and 5.7% for the calorimetry method. The average coefficient of variation between multiple batches was 5.5 % and 7.1 %, for the bound water and calorimetry method, respectively. Note that in this study, the same samples were tested for both calorimetry and bound water, because the samples were removed from the calorimeter and tested for bound water, so the same factor that may have affected the calorimetry results, also affected the bound water.

Based on the variability, the easiness of performing the test, and the ability to use glass containers, eliminating the need to seal the samples, the bound water method was found to be preferable.

Individual test results are presented in Appendix E.

7.1.6. Calcium Oxychloride Formation

The reaction between $Ca(OH)_2$, present as a hydration product in cementitious materials, and the chloride ions, present in calcium chloride and magnesium chloride based deicing salts, forms calcium oxychloride (CAOXY) crystals [90], which are believed to play a major role in concrete pavement deterioration, especially at the joints [91]. Since the formation of CAOXY is directly related to the presence of $Ca(OH)_2$, a potential mitigation strategy involves reduction of the $Ca(OH)_2$ content in the paste of the material. This can be achieved by introducing SCMs into the mixture. The efficiency of the SCMs in reducing the CAOXY depends on [92]:

- The amount of cement replaced by the SCM, since it causes a dilution effect, and lowers the $Ca(OH)_2$ produced;
- SCM pozzolanic activity, i.e., its tendency to consume $Ca(OH)_2$ [94];
- SCM binding capacity, i.e., its capability to bind chlorides within the reaction products [95];
- SCM ability to densify the microstructure, reducing the porosity and the pores connectivity, i.e., slowing down the ionic transport within the concrete.

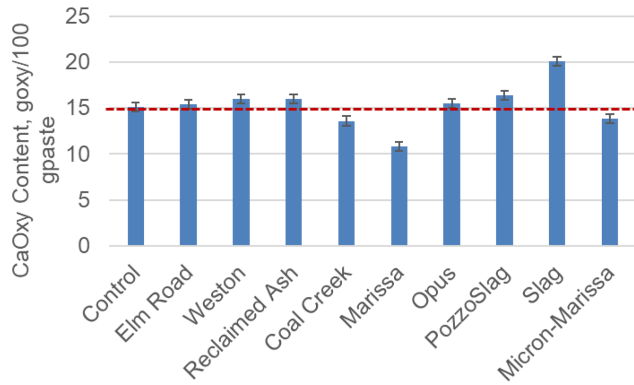


Figure 14 – Calcium Oxychloride formation. The dashed line represents the threshold in AASHTO R 101 [93].

Figure 14 shows the calcium oxychloride formed at 28 days. The threshold in AASHTO R 101 for durable concrete is recommended at 56 days. The best performing material was Marissa, however, the other fly ashes and ASCM are close enough to the threshold that one can assume that by 56 days, the CAOXY will be below the threshold. Surprisingly, slag did not perform as well and no assumption can be made regarding its performance at 56 days.

7.2. Concrete Performance Results

The concrete test results are summarized in this chapter. For complete access to all test results, refer to Appendix E.

7.3.1. Fresh Properties

The dosage of the Type A admixture varied from 3.3 oz/cwt to 4.5 oz/cwt and the slump from 0.75 to 2.00. Slag showed lowest slump, while PozzoSlag showed the highest with 4.0 oz/cwt (Table 16). Reclaimed ash required the lowest dosage to achieve a slump of about 1.50 in. Although Elm Road achieved an acceptable slump, it showed the worst workability under vibration (Table 17), despite the fact that it had a higher cementitious content and the same w/cm of the other mixtures.

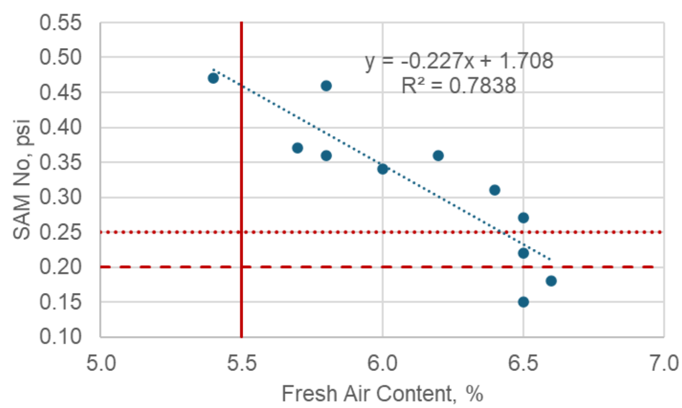


Figure 15 – Fresh air and SAM no. Vertical solid line present WisDOT specified minimum air content. Big dashed line indicates the SAM No. threshold for a good freeze-thaw performance [96]. Small dashed line indicates Wisconsin DOT recommended maximum SAM No.

Fresh air content and the SAM number show the same trend but not a good correlation (Figure 15). Only one mixture showed air content below the WisDOT specification required 7.0 ± 1.5 %. On the other hand, only two mixtures presented acceptable SAM number, i.e., lower than 0.20 psi [96], and only three had SAM number. below the recommended WisDOT threshold. A study showed that higher than a SAM of 0.20 psi does not necessarily indicate that the concrete is not freeze-thaw durable and that the 0.008 in. recommendation is very conservative [97]. However, no petrographic examination was performed on concrete samples to guarantee that the spacing factor for the mixtures with SAM number above 0.20 psi had inappropriate spacing factor (above 0.008 in.). As it will be shown later in this chapter, freeze-thaw resistance testing was performed and indicated adequate freeze-thaw performance for all mixtures.[98]

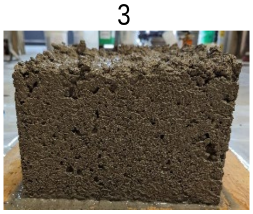
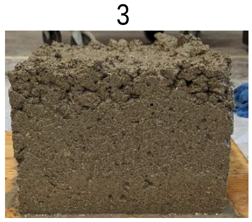
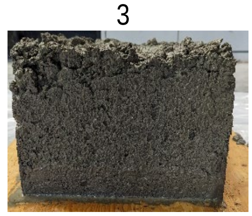
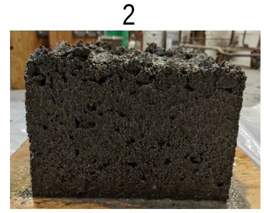
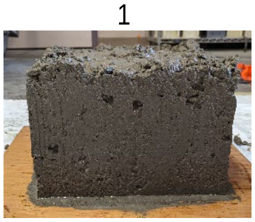
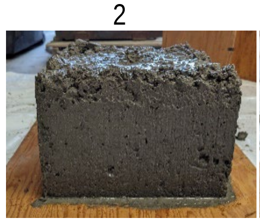
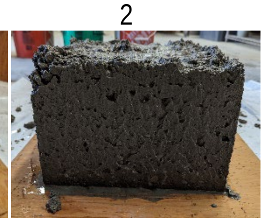
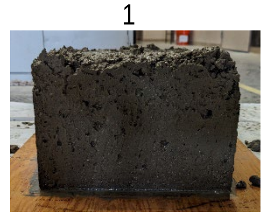
Since Liquid ASCM is an admixture and not a SCM that replaces cement on a mass basis, it was not possible to perform the conventional mortar testing required in ASTM C618, such as setting time. However, it was important to determine if the Liquid ASCM would affect setting time. Hence, AASHTO T 197M/T 197-23 was performed in the control mixture and the Liquid ASCM mixture. The initial setting time was 326 minutes and 322 minutes, for the control and Liquid ASCM mixtures, respectively. The final setting time was 431 minutes and 425 minutes, for the control and Liquid ASCM mixtures, respectively. The results show that both initial and final setting of the control and the Liquid ASCM mixtures were the same.

Table 16 – Fresh Properties and Admixtures Dosages

	Slump, in. (Type A, oz/cwt)		Air Content, % (AEA, oz/cwt)		SAM no., psi		Unit Weight, lb/ft^3		Temperature, °F	
Mix	Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2
Control	1.50 (4.5)	1.50 (4.5)	6.0 (1.1)	6.0 (1.1)	0.34	-	147.7	147.7	59	69
Elm Road	1.00 (4.0)	1.50 (4.5)	6.5 (1.1)	6.0 (1.0)	0.15	-	146.9	147.5	66	66
Weston	1.50 (4.0)	1.50 (4.0)	6.4 (1.0)	6.3 (1.0)	0.31	-	151.7	148.2	70	70
Reclaimed Ash	1.50 (3.6)	1.25 (3.3)	6.6 (1.1)	6.6 (1.0)	0.18	-	145.7	146.5	67	67
Coal Creek	1.75 (3.4)	1.75 (4.0)	5.8 (1.0)	6.0 (1.1)	0.36	-	148.5	148.2	65	66
Marissa	1.50 (4.0)	1.75 (4.1)	5.7 (1.0)	6.0 (1.2)	0.37	-	148.5	148.2	67	67
Opus	1.00 (3.9)	1.25 (3.9)	5.8 (1.0)	6.2 (1.0)	0.46	-	147.7	147.5	66	66
PozzoSlag	2.00 (4.0)	1.50 (4.0)	6.5 (1.0)	6.0 (1.0)	0.27	-	147.0	148.2	66	67
Slag	0.75 (4.0)	1.00 (4.0)	5.5 (1.2)	5.4 (1.2)	-	0.47	150.0	150.1	67	67
Micron3+Marissa	1.50 (4.0)	1.50 (4.0)	6.2 (1.0)	6.2 (1.0)	0.36	-	150.9	148	70	70
Liquid ASCM	2.00 (4.0)	1.80 (4.0)	7.5 (1.0)	6.5 (0.8)	-	0.22	147.3	-	69	NA

Note: SAM was obtained in only one of the two batches.

Table 17 – AASHTO T 396 – Box Test Pictures and Ratings of Selected Mixtures (Mixtures with average rating above 1).

Control				
	2	2	1	1
Elm Road				
	3	3	3	2
Weston				
	1	2	2	1
Marissa				
	1	2	1	2

7.3.2. Mechanical Properties

Compressive Strength

Figure 16 shows the strength development of the mixtures. Coal Creek and Liquid ASCM mixtures (Figure 16 a and c) do not gain much strength after 28 days. On the other hand, after 7 days, the strength gain rates of the Marissa, Micron3+Marissa, slag, and OPUS (Figure 16b) mixtures are higher than the control, especially between 28 and 90 days. The higher strength gain rate indicates the pozzolanic reactions in these mixtures.

Figure 16d shows that by 90 days, the Elm Road, Weston, Marissa, Slag and Micron3+Marissa mixtures achieved or surpassed the control mixture compressive strength. Nonetheless, it is important to highlight that all mixtures achieved much higher strengths than what is normally required (Figure 16d) by WisDOT specification. The necessary 3,000 psi for opening to traffic strength requirement was achieved in 3 days by all mixtures, except for the PozzoSlag mixture. By 7 days, the strengths for all mixtures, except for the PozzoSlag, were much higher than the acceptance compressive strength at 28 days of 3,700 psi[10].

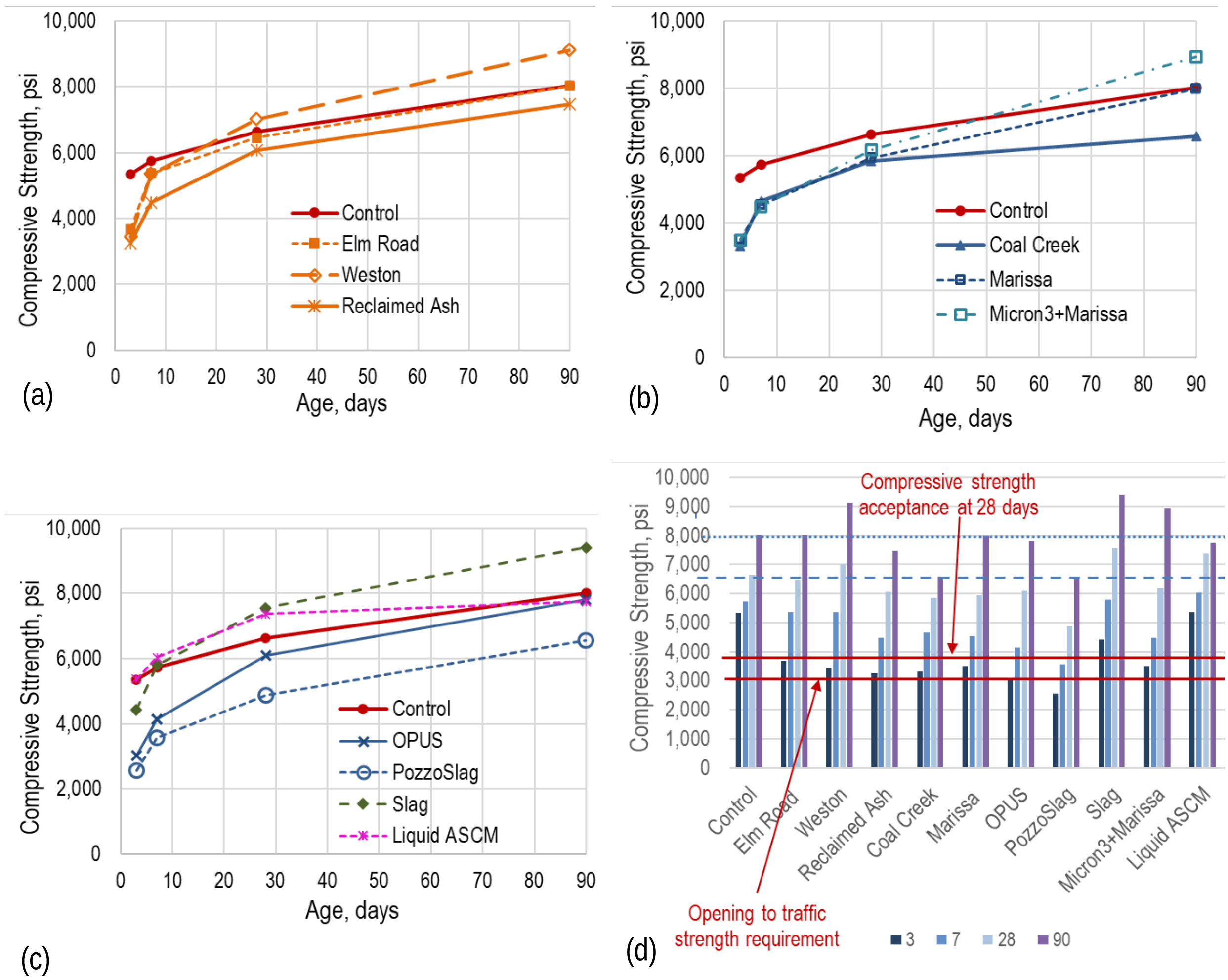


Figure 16 - Compressive strength over time: (a) Class C fly ashes, (b), Class F fly ashes, and (c) all other materials.

Figure 17 shows the cumulative percent gain from one age to the next. It is clear that the control and the Liquid ASCM mixtures reached a maximum of about 20% at 90 days, while all the remaining mixtures, with surpassed 25% by 28 days. The increase from 28 to 90 days for Liquid ASCM is insignificant. The biggest difference between the control and the Liquid ASCM and the remaining mixtures is a more significant percent increase from 28 to 90 days.

The compressive strength from 28 to 90 days is more than 20% for all the mixtures, with exception of Coal Creek and Liquid ASCM. This increase is even more significant for Marissa and PozzoSlag, with an increase of over 34% and for Micron3+Marissa, with an increase of about 45%.

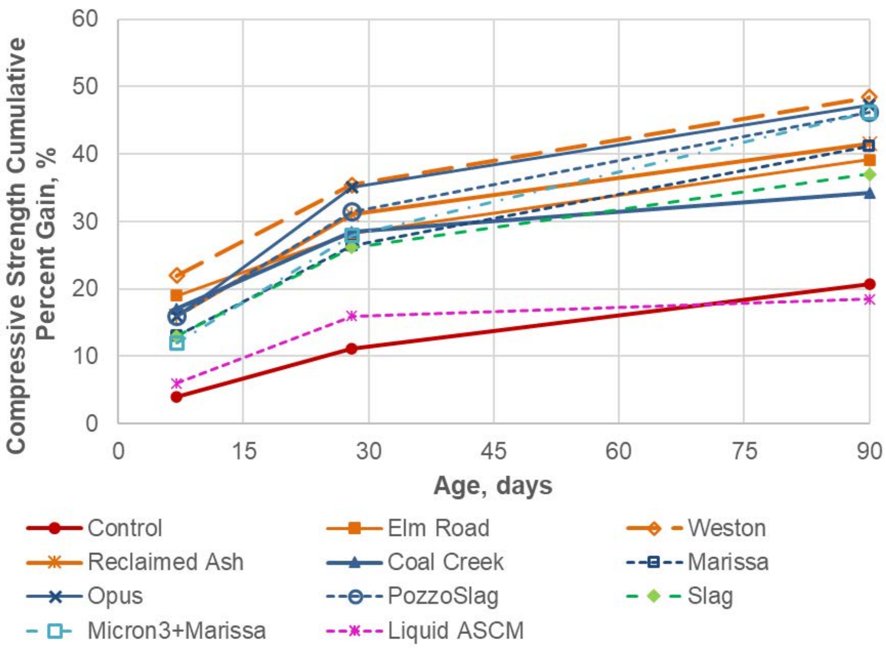


Figure 17 - Cumulative percent gain of compressive strength from age to age.

Flexural Strength

Figure 18a shows that control, Elm Road, Weston, Reclaimed Ash, slag, and Liquid ASCM mixtures achieved the 28-day flexural strength acceptance by 7 days, while the others, with exception of the PozzoSlag mixture, surpassed this threshold by 28 days.

An ANOVA TukeyHSD/Kramer statistical analysis, with 95% confidence, showed that the apparent difference in strengths displayed Figure 18 may be misleading. The statistical analysis showed that the flexural strength at 3 days is statistically the same for all mixtures, except for the control. At 3 and 7 days, the strength of the control was statistically higher than all the other mixtures. In addition, at 7 days, the statistical analysis split the remaining mixtures into two groups, each of them comprised of mixtures with statistically similar flexural strengths. The first group with higher flexural strength included Elm Road, Weston, Reclaimed Ash, Slag and Liquid ASCM, and the second group with the lowest flexural strength, included Marissa, Micron3+Marissa, Coal Creek, OPUS, and PozzoSlag. At 28 days, the statistical analysis showed that there was no difference in flexural strength among the mixtures, with exception of the PozzoSlag, that showed lower flexural strength. The slag mixture differed only from the Marissa and Liquid ASCM mixtures.

The mixtures in Figure 18b surpassed the flexural strength acceptance criterion of 650 psi by 7 days. The mixtures in Figure 18c surpassed the flexural strength acceptance criterion before 28 days. On the other hand, Figure 18d shows that slag and Liquid ASCM surpassed the flexural strength acceptance criterion by 7 days, OPUS surpassed this criterion before 28 days, and PozzoSlag did not achieve the criterion by 28 days. Figure 18b, c, and d also show that the flexural strength gain rate between 7 and 28 days of all mixtures was higher than that of the control mixture.

The results of the statistical analysis can be found in Appendix F.

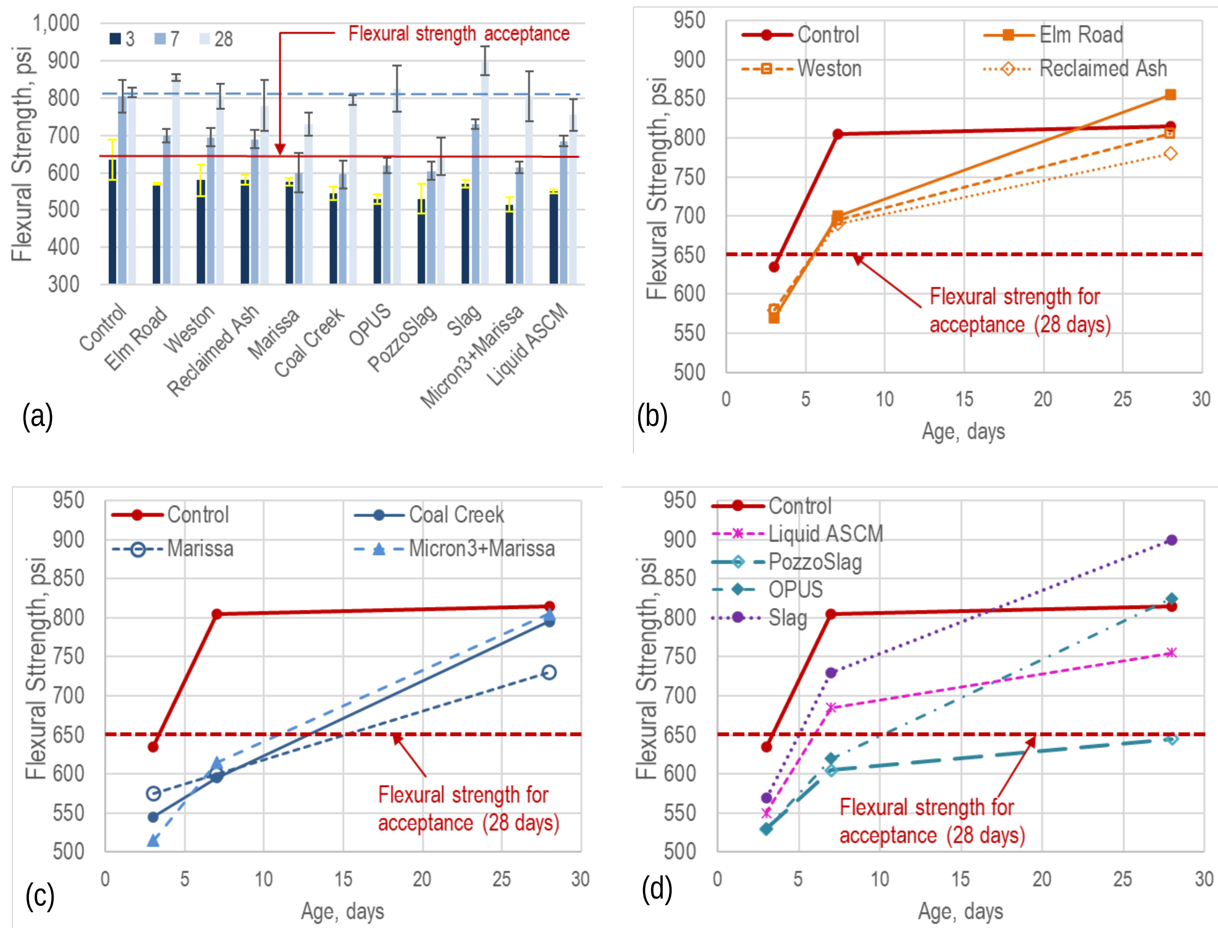


Figure 18 – (a) Flexural strength at 3, 7, and 28 days. The dashed line indicates the 28 days flexural strength of the control mixture. (b), (c), and (d) Strength development.

7.4. Durability Related Properties

Free Drying Shrinkage

Figure 19 shows the free shrinkage. In this test, specimens were demolded at 24h after casting and immediately exposed to drying conditions as described in ASTM C157/C157M-17[84]. Since the Elm Road, Marissa and Coal Creek mixtures had a higher cementitious content than the other mixtures, their change in length was adjusted for a paste content equivalent to the 530 lb/yd^3 total cementitious content.

Shrinkage ranged from 0.026 % to 0.050%, when specimens were cured for only one day before being exposed to drying. Some specifications, such as MnDOT for bridge decks, specify a maximum shrinkage of 0.040%. However, this limit is specified for specimens cured for 7 days before being exposed to drying. Specimens cured for only one day are expected to present the worst-case scenario, so if they were cured for 7 days, most of the mixtures in this study would probably pass because they are already close to this 0.040% limit, with exception of Reclaimed Ash and Slag.

The ANOVA TukeyHSD/Kramer statistical analysis showed that the control and the Liquid ASCM mixtures presented statistically lower shrinkage than the other mixtures, but they were considered similar between the two of them. On the other hand, the remaining mixtures, except for the Reclaimed Ash and Slag showed statistically similar shrinkage. The shrinkage of the Reclaimed Ash and Slag mixtures were statistically the highest of all. The complete statistical analysis can be found in Appendix F.

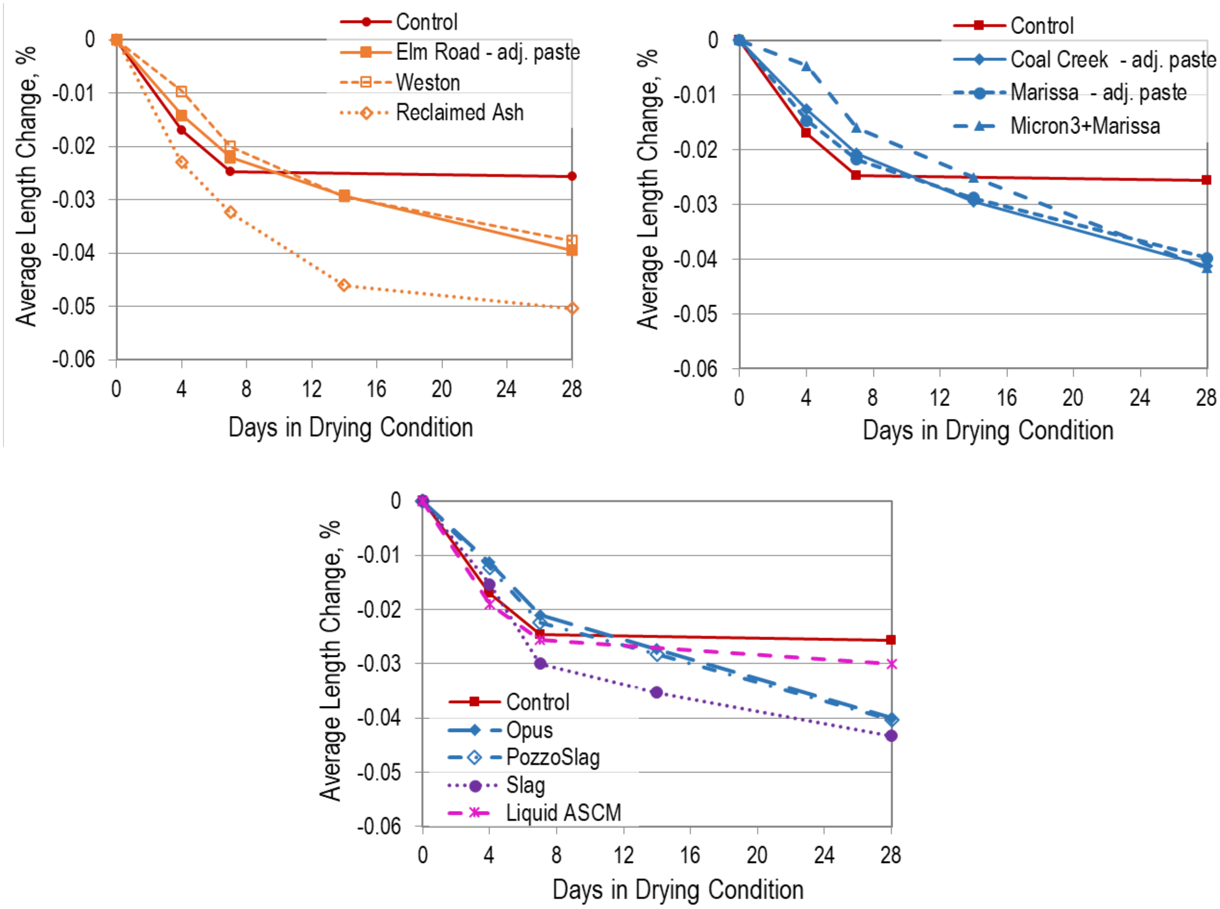


Figure 19 – Length change during drying.

Freeze-Thaw Resistance

Figure 20a shows a very good freeze-thaw resistance after 300 cycles for all mixtures. There was no difference in performance among the mixtures. Figure 20b shows that the only difference was that the Elm Road, Marissa and Slag mixtures presented statistically lower mass loss during testing when compared to the other mixtures.

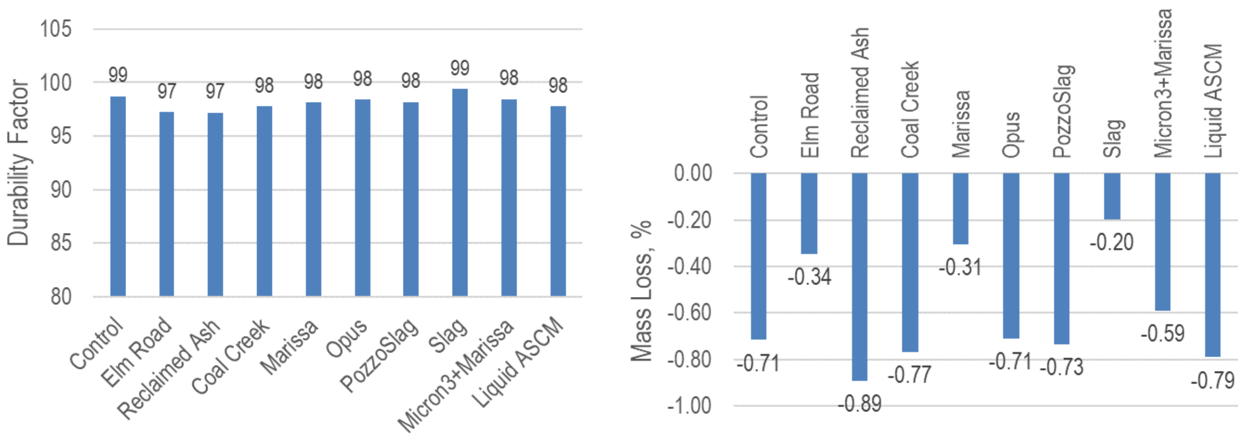


Figure 20 – Freeze-thaw resistance. (a) Durability factor at 300 cycles, (b) Mass loss at 300 cycles.

Surface Resistivity

The surface resistivity, as determined according to WTM T358[99], a modified version of AASHTO T 358-22[86], and the chloride ion penetrability classes, also defined in WTM T358, are presented in Figure 21. At 28 days, all mixtures but slag, are within the moderate penetrability range. The Control mixture and the Liquid ASCM mixture remain in this category through 180 days. At 90 days, all the mixtures, with the exception of Control and Liquid ASCM, where found in the low penetrability range. By 180 days, Elm Road, Weston, Coal creek, Marissa, Opus, PozzoSlag and Micron3+ Marissa achieved the very low penetrability range.

Figure 22 shows the increase in resistivity over time. It is clear that for most of the mixtures, with the exception of the control and Liquid ASCM, there is a significant increase in resistivity beyond 28 days. Slag and Reclaimed ash increase 14% and 26% from 28 to 90 days, while the other binary and ternary mixtures, with exception of Liquid ASCM< increase up to 47% over the same period. More interesting is that this increase continues significantly beyond the 90 days. As shown by the steep curves in Figure 22, Micron3+ Marissa, Opus, Marissa, PozzoSlag, Coal Creek and Weston keep gaining considerable resistivity up to 365 days. Except for the Control, Liquid ASCM, Slag, Reclaimed Ash, and Elm Road, the resistivity increase for the other mixtures from 91 to 180 days and from 180 to 365 days are higher than the increase between 28 and 91 days. It shows the inadequacy of specifying resistivity values for ages below 90 days. Similar behavior was found for compressive strength.

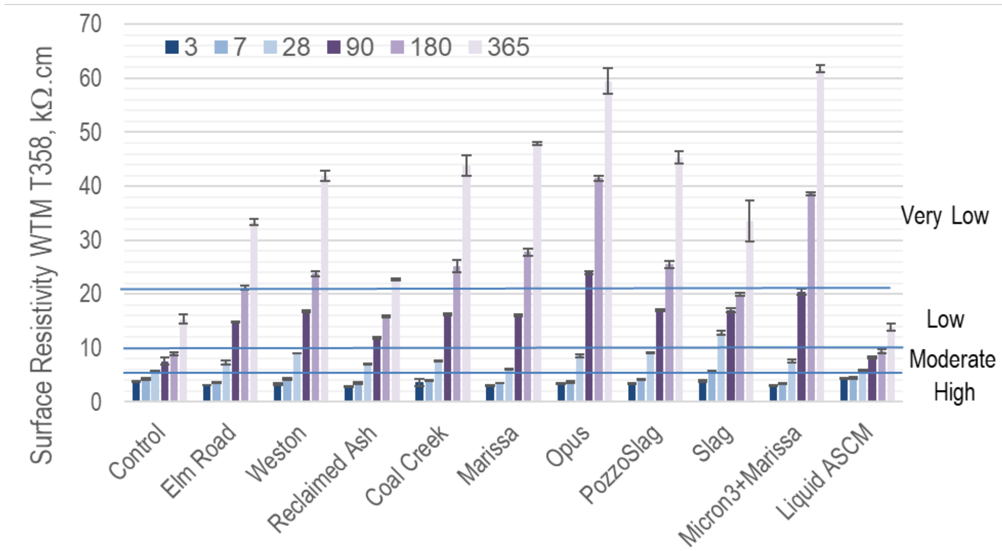


Figure 21 – WTM T358: Surface resistivity test results and chloride ion penetrability classes.

At 3 days, it is difficult to differentiate mixtures. They all show very low surface resistivity. At 7 days, statistical analysis starts showing some differentiation but since the surface resistivity of all the mixtures is still so low, it is not advisable to come to any conclusion. Statistically, at 28 days, the Control, Marissa, and Liquid ASCM mixtures showed the lowest surface resistivity. A group with statistically slightly higher resistivity included the Elm Road, Coal Creek and Micron3+Marissa mixtures. Following, a statistically higher surface resistivity than the previous group was the group that included the Weston, OPUS, and PozzoSlag mixtures. The Slag mixture was statistically different than all the other mixtures and showed the highest 28-day surface resistivity.

At 90 days, statistical analysis showed that the surface resistivity of the Weston, Coal Creek, Marissa, PozzoSlag, and Slag mixtures were similar. All the remaining mixtures were statistically different than each other, with the Control and Liquid ASCM mixtures being statistically the same and showing the lowest surface resistivity. Statistically, OPUS showed the highest 90-day surface resistivity. At 180 and 365 days, the Control and Liquid ASCM mixtures still had the surface resistivity statistically the same and the lowest of all mixtures, the Weston, Coal Creek and PozzoSlag mixtures had surface resistivities statistically the same but the surface resistivities of all the other mixtures were statistically different, with the OPUS and Micron3+Marissa showing the highest surface resistivities of all.

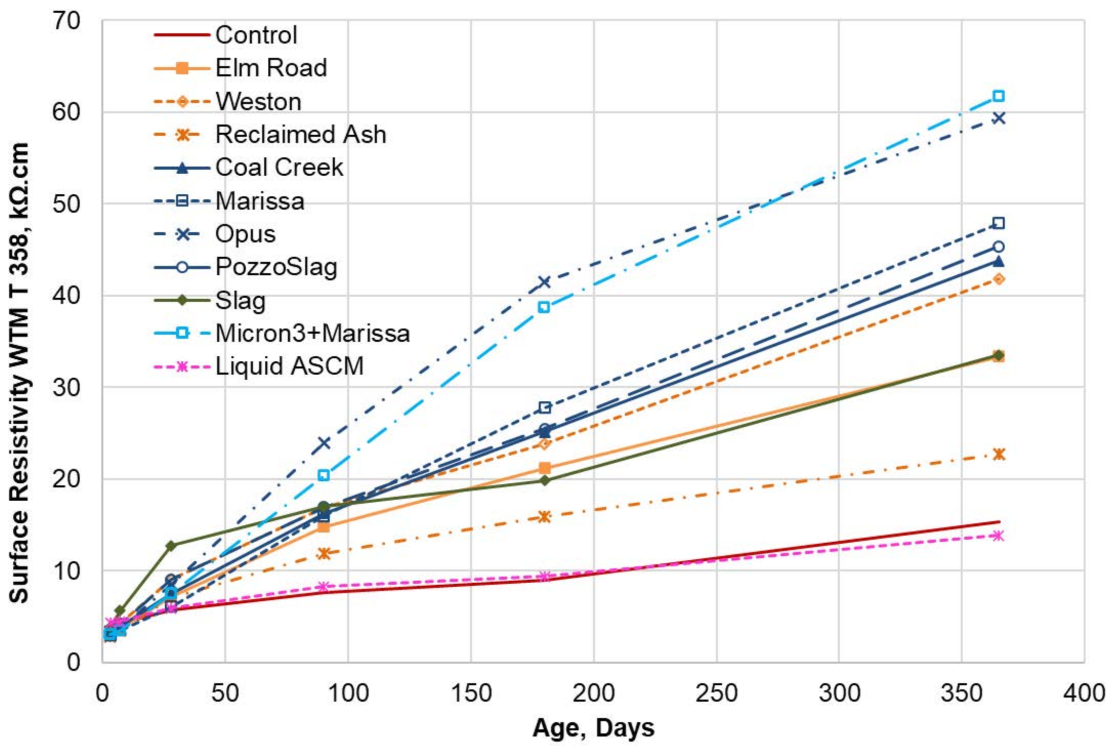


Figure 22 – Surface resistivity over time.

8.0 Discussion

8.1. Relationship between Loss on Ignition and Foam Index

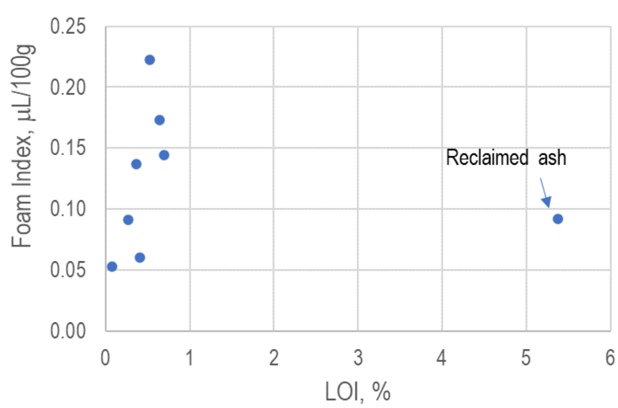


Figure 23 – Relationship between LOI and Foam Index.

As mentioned in Section 4.6, LOI does not correlate with AEA demand. This was confirmed in this study. Reclaimed Ash had over 6 times the LOI of the other SCMs but, at the same time, a low Foam Index (Figure 23).

The lack of relationship between LOI and AEA demand is because AEA demand is a function of active carbon and LOI measures all unburned carbon. In addition, the presence of sulfides, sulfur and some iron minerals could also oxidize and gain weight to reduce the LOI [100], [101].

8.2. Relationship between Loss on Ignition and Concrete AEA Requirements

Figure 24a shows that there is no relationship between LOI and the AEA required to achieve acceptable air content and that the mixtures required about the same AEA dosage, independently of the LOI. It is clear that the requirement of maximum LOI is not a good predictor of concrete performance.

8.3. Relationship between Foam Index and Concrete AEA Requirements

Figure 24b shows the lack of relationship between the foam index and the AEA required to achieve acceptable air content. While foam index had a wide range depending on the material, the AEA dosage varied from 1.0 to 1.1 oz/cwt. Foam Index was not capable of realistically reflecting the concrete behavior. Foam index may be a good indicator of potential air problems, but since none of the materials in this study presented air issues, the foam index was not relevant.

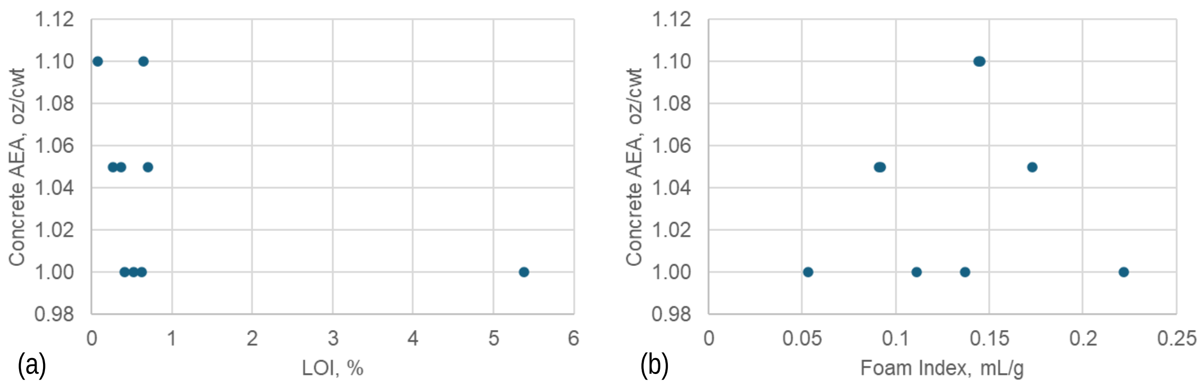


Figure 24 – Relationship between (a) LOI and concrete dosage of AEA and (b) foam index and concrete dosage of AEA.

8.4. Relationship between Mortar Water Requirement and Concrete Workability

There was no clear correlation between the water requirement and the concrete workability.

8.5. Relationship between modified SAI and Crystallinity

Interestingly, amorphous content did not relate to modified SAI. It is believed that it is the amorphous content and phases in most SCMs that drive reactivity. So, it was expected that the lowest amorphous content would result in poorest strength performance and vice versa. However, this is not what was observed. For example, Weston presented the lowest amorphous content but at 28 days, its strength surpassed that of the control, while Marissa had the highest amorphous content, but it only surpassed the control strength at 90 days. The fineness of these materials does not seem to justify the unexpected results.

8.6. Relationship between modified SAI and Chemical Composition

No correlation was found between modified SAI and chemical composition. This is probably because the modified SAI is a result of not only of the chemical composition but all the other properties that affect the reactivity and the microstructure formation of the cement paste.

8.7. Relationship between Chemical Composition and Reactivity

Figure 25 shows that there is a trend between the reactivity tests and the sum of oxides. However, the correlation between them is not good. This is because the reactivity test reflects not only the material's chemistry but also other important properties, such as particle size and crystallinity. Consequently, it is a better measure of the chemical behavior of the material.

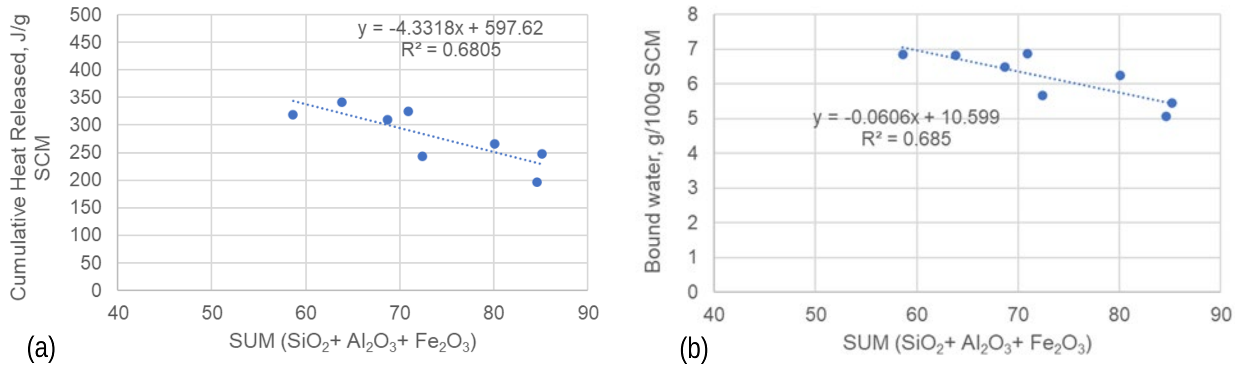


Figure 25 – Relationship between the sum of oxides and the reactivity test.

8.8. Relationship between modified SAI and Reactivity

Figure 26 shows that there is a relationship between the results obtained according to ASTM C1897 and the modified SAI, although the correlation may not be that good. For the cumulative heat released, the slag mixture seemed to perform differently than the other mixtures, while this behavior was not shown with the bound water.

For the threshold for 90% confidence suggested by Londono-Zuluaga et al.[50], one obtains a modified SAI of 73% and 76%, using the equations in Figure 26a and b, respectively. This is an indication that both methods in ASTM C1897 are good indicators of reactivity and may replace the need to perform SAI and wait for 28 days or longer.

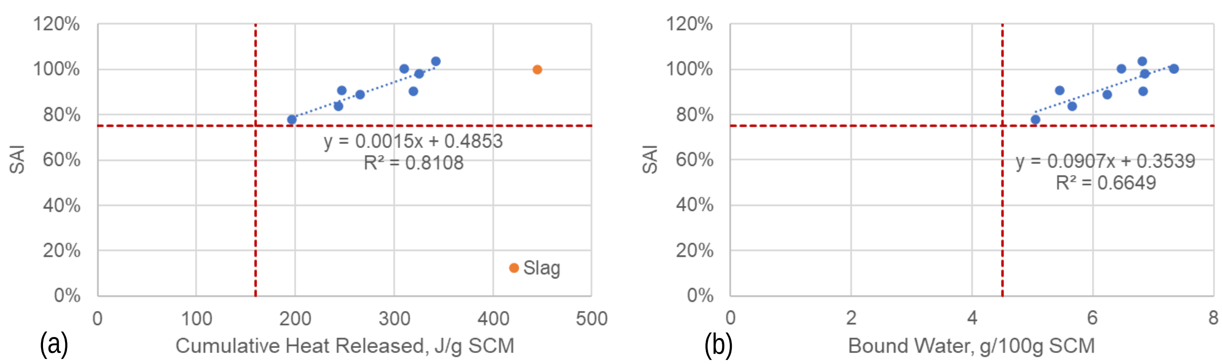


Figure 26 – Correlation between modified SAI and ASTM C1897 (a) Cumulative heat released and (b) Bound water. Dashed lines represent the SAI 75% threshold and the respective thresholds for 90% confidence for cumulative heat and bound water, as per Londono-Zuluaga et al.[50].

8.9. Relationship between Modified SAI and Concrete Compressive Strength

Figure 27 shows the relationship between the modified SAI and the ratio between the compressive strength of the SCM mixtures over the strength of the control mixture for concrete. PozzoSlag and Slag seem to show a behavior different than the other mixtures, but even if they are removed from the analysis, the correlation between the mortar modified SAI and the concrete SAI is not very good but shows a trend. Consequently, when comparing different mixtures, the modified SAI may be a good tool to rank mixtures in terms of strength.

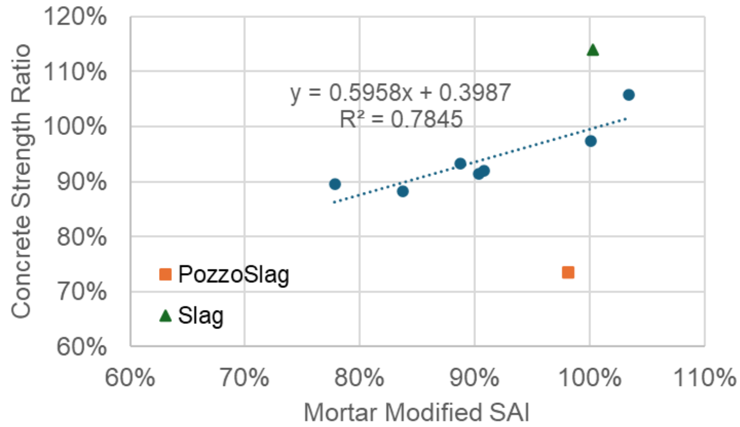


Figure 27 – Concrete compressive strength ratio in relation to the modified SAI.

8.10. Relationship between Concrete Compressive Strength and Flexural Strength

Figure 28 shows that there is a relatively good correlation between compressive and flexural strength when Liquid ASCM is removed from the analysis. It is clear that for Liquid ASCM, at that for the same compressive strength, the flexural strength is lower than that of the other mixtures. This may be due to the bond between paste and coarse aggregate, but an in-depth assessment would be needed to confirm it. Note that this relationship may change for a different coarse aggregate maximum size and type[102], [103].

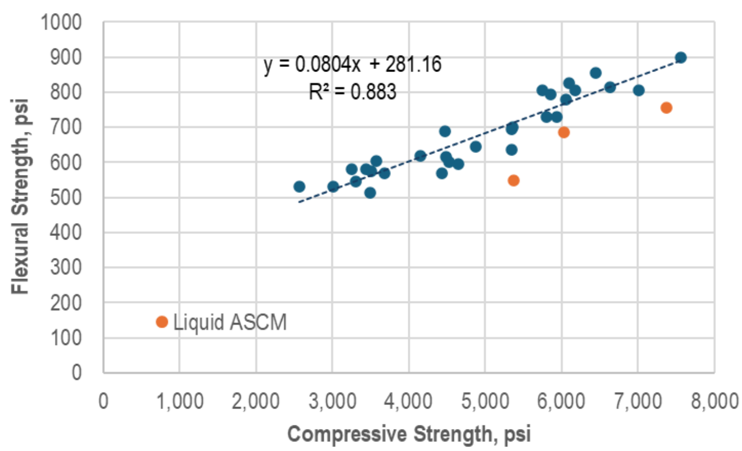


Figure 28 – Relationship between compressive and flexural strength for 3, 7, and 28 days.

8.11. Relationship between Concrete Compressive Strength and Resistivity

Figure 29 shows the correlation between compressive strength and surface resistivity. While compressive strength is a function of the paste microstructural, the bond between the paste and the coarse aggregate, as well as the coarse aggregate strength, resistivity is a function of the microstructure of the paste and the pore solution in it. This explains why the correlation between them is good but not perfect.

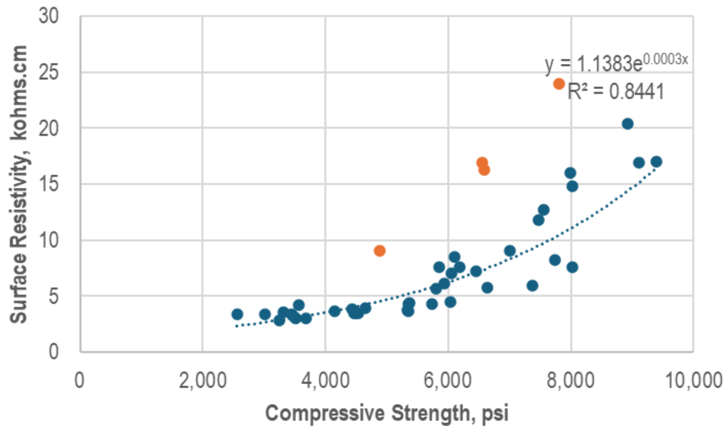


Figure 29 – Relationship between compressive strength and surface resistivity. Points in orange represent data that did not follow the same trend as the other mixtures.

8.12. SAM Threshold for Freeze-Thaw Resistant Concrete

As seen in Table 16, the SAM number varied from 0.18 to 0.47. WisDOT recommends a SAM below 0.25, however, even the mixtures that surpassed this value performed very well in the freeze-thaw testing (Figure 20). This shows that the 0.25 threshold may be very conservative.

9.0 Recommendations

This section summarizes the recommendations for consideration by WisDOT. These recommendations are based on the results of this study.

9.1. LOI

In section 7.1.4, it was shown that the LOI is not a good indicator of AEA requirement or air stability for fly ashes. However, 501.2.4.2.2.1 of the 2024 WisDOT Specification limits LOI to 2%.

Recommendation: Remove the requirement for LOI and reword 501.2.4.2.2.1 as follows:

Obtain, from the fly ash manufacturer, a copy of the certified report of test or analysis made by a qualified independent laboratory, showing compliance with ASTM C618 for the appropriate fly ash class. Submit the report to the engineer with the mixture proportion, at least 7 business days before use.

9.2. SAM

The construction materials manual (CMM) attachment 870-2 reads:

"Although currently there are no contractual specification limits, an acceptable SAM number is ≤0.25".

In this study, concretes with SAM of up 0.47 performed well in freezing and thawing.

Recommendation: Obtain more information and possibly establish a SAM limit as 0.25 appears to be too restrictive.

9.3. Class F Fly Ash

In this study, Class F fly ashes performed well and there are no main issues reported particular to Class F fly ashes. However, 501.2.4.2.2.3 of the Specification limits the replacement rate of fly ashes not in the approved product list (APL) to 15%. Additionally, the specification allows for up to 30% of blended fly ashes. Blended fly ashes could be a blend that results in a class F fly ash, so there is a contradiction between requirements.

Recommendation: Eliminate the APL for Class F fly ashes and allow the use of up to 30% of Class F fly ashes that comply with ASTM C618, with the exception of SAI. It is recommended to replace the SAI with the modified SAI performed in this study.

9.4. Blended Fly Ashes

Section 501.2.4.2.5 of the Specification requires blended fly ashes to comply with ASTM C1697. Though, C1697 requires that all constituents used in the manufacture of the blended SCM to conform to their applicable specification. The need for the individual constituents to comply with their applicable specification is totally unnecessary and prevents the use of constituents that, when blended with other constituents in the right proportions, might yield good quality SCMs.

Recommendation: Remove the need for the individual constituents to comply with their applicable specification, as long as the blended SCM ultimately complies with the applicable specification, in addition to Table 3 of C1679, with the exception of the SAI, which should be replaced by the modified SAI.

9.5. Alternative Supplementary Cementitious Materials

According to ASTM C1709, ASCMs are inorganic materials that react pozzolanically or hydraulically, and beneficially contribute to concrete properties, and don't meet Specifications C618, C989/C989M, C1240 and C1866/C1866M. No conformance with the referenced specifications means that the material does not meet the chemical and/or physical requirements, and/or the material definition. For example, Opus doesn't comply with ASTM C618, despite meeting the chemical and physical requirements, because it is not a coal ash, so it is considered an ASCM.

Currently, 501.2.4.3 of the Specification requires testing the ASCMs according to ASTM C1709. Nevertheless, ASTM C1709 is a guide, thus just gives suggestions of tests to perform, including a field trial, which is not always feasible. Additionally, because it is a guide, it doesn't provide compliance requirements or limits for each of the properties. Hence, it does not provide guidance if the material should be considered acceptable or not.

Recommendation: A framework for evaluation of ASCM and guidance on acceptability requirements are presented herein (Figure 30). The evaluation starts with reactivity testing (ASTM C1897). If the material presents reactivity below the 90% confidence of 160 J/g of SCM (procedure A) or 4.5/100 g of SCM (procedure B) [50], the material is rejected and no further testing is required.

If it passes this requirement, a control mortar containing the maximum allowed replacement rate of C618, or C989/C989M, or C1240, or C1697 (whichever is most similar to the ASCM, based on the chemical composition) and a test mixture containing ASCM at the same replacement rate. If the modified SAI is below 90%, the material is rejected for use, otherwise, the evaluation continues. Note that this SAI does not compare the test mixture with a plain mixture but with a mixture containing SCM.

1. If the ASCM complies with the chemical and physical requirements of C618, or C989/C989M, or C1240 (Figure 30a), then two mixtures with a Type I, II, I/II or IL cement are prepared: a control, a grade A mixture containing a SCM used in Wisconsin at the maximum allowed replacement rate, and a test mixture, a mixture containing the ASCM at the same replacement rate. The concrete performance is evaluated by:
   a. Conducting fresh property tests:

    - Slump (AASHTO T 119M/T 119)
    - Air content (AASHTO T 395)
    - Box Test (AASHTO T 396)
    - Setting time (ASTM C403/C403M)
    - SAM (AASHTO T 395)
   b. Conducting mechanical property tests:
      - Compressive strength at 7, 28, and 90 days (AASHTO T 22M/ T 22)
      - Flexural strength at 7, 28, and 90 days (AASHTO T 97M/ T 97)
   c. Conducting durability related tests:
      - Freeze-thaw resistance (ASHTO T 161, procedure A)
      - Shrinkage, 7 days of curing followed by 28 days of drying (modified ASTM C157/C157M)
      - Surface resistivity, 90 days (WTM T358[99])
   d. Comparing the results with the requirements in Table 18. If the ASCM meets the requirements it is allowed for use.
2. If the ASCM does not comply with the chemical and physical requirements of C618, or C989/C989M, or C1240 (Figure 30b), an approach similar to ASTM C494/C494M is applied. Three batches of the control and three of the test mixtures are prepared and tested. This will take into account the variability from one batch to another. On a given day, the same number of batches of the control and test concrete should be made. Then, the concrete performance is evaluated by conducting the fresh, mechanical and durability tests and comparing with the requirements in Table 18:
   a. Fresh property tests:
      - Slump (AASHTO T 119M/T 119)
      - Air content (AASHTO T 395)
      - Box Test (AASHTO T 396)
      - Setting time (ASTM C403/C403M)
      - SAM (AASHTO T 395)
   b. Conducting mechanical property tests:
      - Compressive strength at 7, 28, 90, and 180 days (AASHTO T 22M/ T 22)
      - Flexural strength at 7, 28, 90, and 180 days (AASHTO T 97M/ T 97)
   c. Conducting durability related tests:
      - Freeze-thaw resistance (ASHTO T 161, procedure A)
      - Shrinkage, 7 days of curing followed by 28 days of drying (modified ASTM C157/C157M)
      - Surface resistivity, 90 days (WTM T358[99])
3. The creation of an APL for ASCMs is recommended, but if a material that is not part of the APL is suggested for use in a specific project, the framework above can be applied and later the ASCM can be added to the APL list.

Table 18 – Suggested requirements for acceptance of ASCM.

Property	Requirements
Slump, max	2.5 in.
Air Content	7.0 ± 1.5 %, using manufacturer recommended dosage of AEA
Box Test	Average rate ≤ 2.5
Setting time	Not earlier than 1 h of control, not later than 1 h of control
SAM	Report only
Compressive strength	90% of control
Flexural strength	90% of control
Relative durability factor	80%
Length change	More research is needed
Surface resistivity	90% of control and low penetrability at 90 days
Other	If there is a reason to believe that the material is prone to specific deterioration mechanisms, the ASCM shall perform as well as the grade A concrete for that mechanism.

9.6. Qualification Testing Ages

In general, it is common practice in the industry to have concrete qualification based on 28 days test results. Nonetheless, as was shown in this project, some SCM and ASCM react slower than cement and conventional SCMs and if they are qualified based on 28 testing, they may not pass the minimum requirements or they may be perceived as a low quality SCM. Still, these SCMs and ASCMs may produce good quality concretes.

Recommendation: Increase the qualification age to 90 days, if the results at 28 days do not meet the requirements.

9.7. Shrinkage

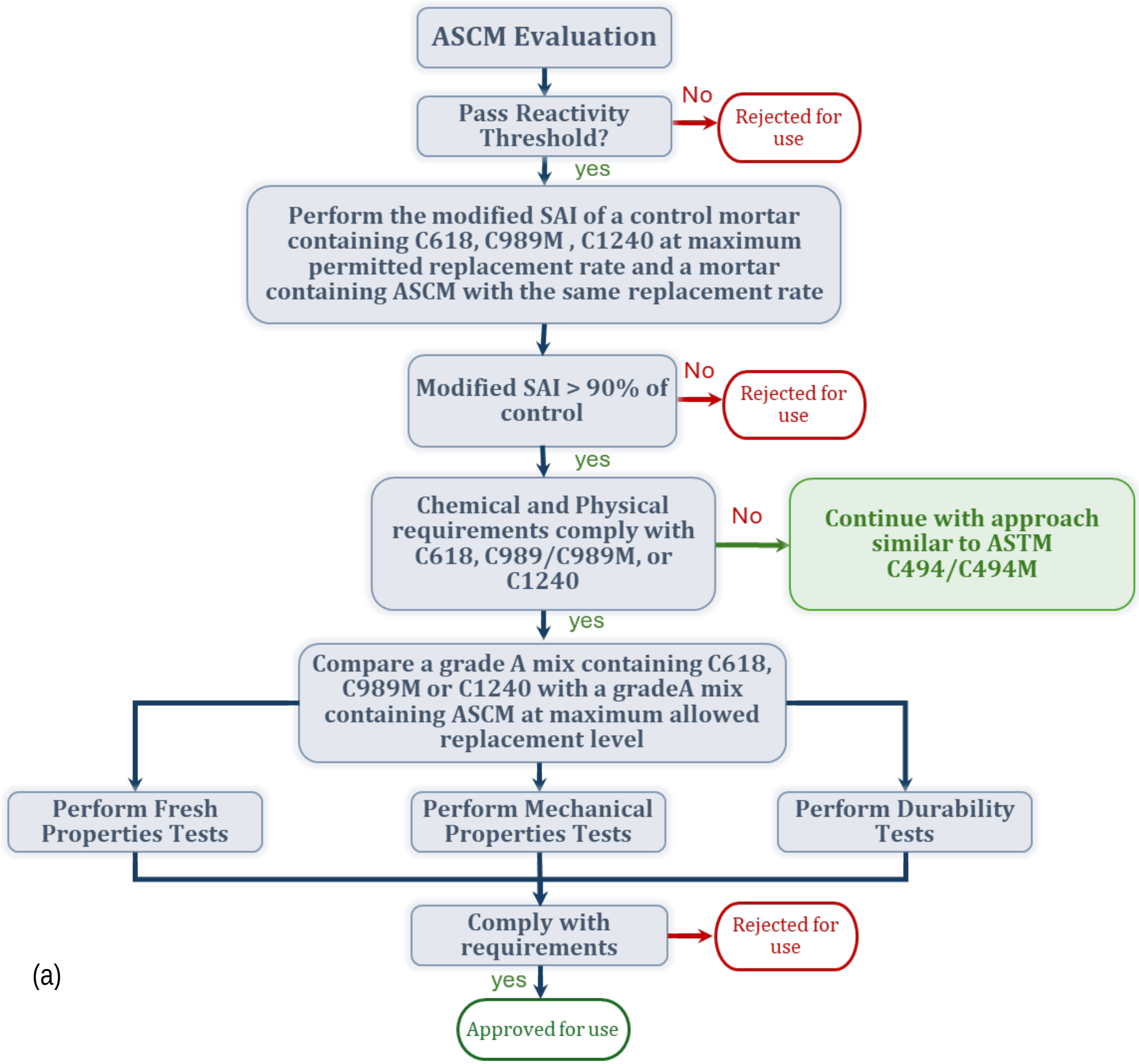
In this study, free shrinkage was performed. Nevertheless, in order to evaluate the results properly, a threshold for acceptable shrinkage is needed, thus more research is needed.

Recommendation: Perform comprehensive research on shrinkage behavior, including estimation of field performance and cracking probability.

9.8. Resistivity

Currently, there are no qualification requirements related to resistivity.

Recommendation: Add qualification requirement of low penetrability at 90 days, according to WRM T358.


ASCM Evaluation
Pass Reactivity Threshold?
No
Rejected for use
yes
Perform the modified SAI of a control mortar containing C618, C989M , C1240 at maximum permitted replacement rate and a mortar containing ASCM with the same replacement rate
Modified SAI > 90% of control
No
Rejected for use
yes
Chemical and Physical requirements comply with C618, C989/C989M, or C1240
No
Continue with approach similar to ASTM C494/C494M
yes
Compare a grade A mix containing C618, C989M or C1240 with a gradeA mix containing ASCM at maximum allowed replacement level
Perform Fresh Properties Tests
Perform Mechanical Properties Tests
Perform Durability Tests
Comply with requirements
Rejected for use
yes
Approved for use

(a)

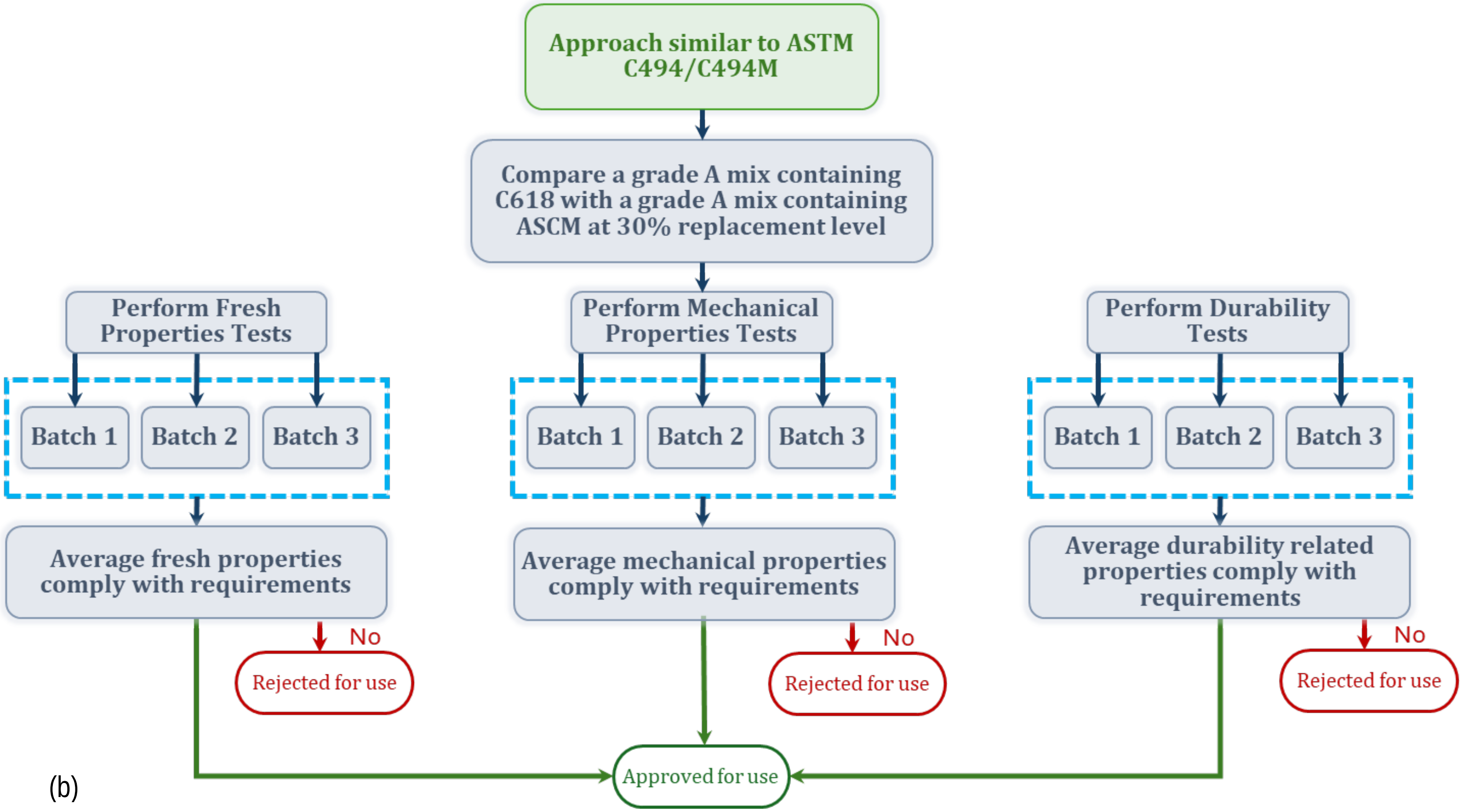


Figure 30 – Framework to evaluate ASCM.

10.0 References

[1] American Road & Transportation Builders Association, “Production and Use of Coal Combustion Products in the U.S.,” 2015.

[2] I. Diaz-Loya, M. Juenger, S. Seraj, and R. Y. Minkara, “Extending supplementary cementitious material resources: Reclaimed and remediated fly ash and natural pozzolans,” *Cem. Concr. Res.*, vol. 101, pp. 44–51, 2019.

[3] ASTM C618-23, “Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.” ASTM International, West Conshohocken, PA, 2023.

[4] ASTM C1709-18, “Standard Guide for Evaluation of Alternative Supplementary Cementitious Materials (ASCM) for Use in Concrete.” ASTM International, West Conshohocken, PA, 2018.

[5] ASTM C989/C989M-24, “Standard Specification for Slag Cement for Use in Concrete and Mortars.” ASTM International, West Conshohocken, PA, 2024.

[6] ASTM C1240-20, “Standard Specification for Silica Fume Used in Cementitious Mixtures.” ASTM International, West Conshohocken, PA, 2020.

[7] ASTM E3183-19, “Standard Guide for Harvesting Coal Combustion Products Stored in Active and Inactive Storage Areas for Beneficial Use.” ASTM International, West Conshohocken, PA, 2019.

[8] CAN/CSA-A3001, “‘Cementitious materials for use in concrete.’” Canadian Standards Association, Mississauga, Ontario, Canada, 2018.

[9] J. Tanesi, A. Ardani, R. Meininger, and M. Nicolaescu, “Evaluation of High-Volume Fly Ash (HVFA) Mixtures (Paste and Mortar Components) Using a Dynamic Shear Rheometer (DSR) and Isothermal Calorimeter, PB2012-112546,” Springfield, VA, 2012.

[10] Wisconsin Department of Transportation, “Standard Specifications for Highway and Structure Construction.” Wisconsin Department of Transportation, Bureau of Project Development, 2024.

[11] ASTM C1697-21, “Standard Specification for Blended Supplementary Cementitious Materials.” ASTM International, West Conshohocken, PA, 2021.

[12] ASTM C1866/C1866M-22, “Standard Specification for Ground-Glass Pozzolan for Use in Concrete.” ASTM International, West Conshohocken, PA, 2022.

[13] AASHTO M 295-21, “Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.” 2021.

[14] AASHTO M 302-22, “Standard SpecificationSlag Cement for Use in Concrete and Mortars.” 2022.

[15] AASHTO M 307-22, “Standard Specification for Silica Fume Used in Cementitious Mixtures.” American Association of State Highway and Transportation Officers, 2022.

[16] AASHTO M 321-04(2021), “Standard Specification for High-Reactivity Pozzolans for Use in Hydraulic-Cement Concrete, Mortar, and Grout.” American Association of State Highway and Transportation Officers, 2021.

[17] M. Tsui-Chang, P. Suraneni, L. Montanari, and W. J. Weiss, “Determination of chemical composition and electrical resistivity of expressed cementitious pore solution using X-ray Fluorescence,” *ACI Mater. J.*, 2017.

[18] S. Ramanathan, M. Kasaniya, M. Tuen, M. D. A. Thomas, and P. Suraneni, “Linking reactivity test outputs to properties of cementitious pastes made with supplementary cementitious materials,” *Cem. Concr. Compos.*, vol. 114, p. 103742, Nov. 2020, doi: 10.1016/j.cemconcomp.2020.103742.

[19] D. Glosser, P. Suraneni, O. B. Isgor, and W. J. Weiss, “Using glass content to determine the reactivity of fly ash for thermodynamic calculations,” *Cem. Concr. Compos.*, vol. 115, p. 103849, Jan. 2021, doi: 10.1016/j.cemconcomp.2020.103849.

[20] X. Wirth, D. Benkeser, N. N. N. Yeboah, C. R. Shearer, K. E. Kurtis, and S. E. Burns, “Evaluation of Alternative Fly Ashes as Supplementary Cementitious Materials,” *ACI Mater. J.*, vol. 116, no. 4, Jul. 2019, doi: 10.14359/51716712.

[21] ASTM C311/C311M-22, “Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete.” ASTM International, 2022.

[22] P. Suraneni, L. Burris, C. Shearer, and R. D. Hooton, “ASTM C618 Fly Ash Specification: Comparison with Other Specifications, Shortcomings, and Solutions,” *ACI Mater. J.*, vol. 118, no. 1, Jan. 2021, doi: 10.14359/51725994.

[23] R. D. Kalina, S. Al-Shmaisani, R. D. Ferron, and M. C. G. Juenger, “False Positives in ASTM C618 Specifications for Natural Pozzolans,” *ACI Mater. J.*, vol. 116, no. 1, Jan. 2019, doi: 10.14359/51712243.

[24] ASTM C595/C595M-23, “Standard Specification for Blended Hydraulic Cements.” ASTM International, 2023.

[25] S. W. Dean, D. P. Bentz, A. Durán-Herrera, and D. Galvez-Moreno, “Comparison of ASTM C311 Strength Activity Index Testing versus Testing Based on Constant Volumetric Proportions,” *J. ASTM Int.*, vol. 9, no. 1, p. 104138, 2012, doi: 10.1520/JAI104138.

[26] S. Donatello, M. Tyrer, and C. R. Cheeseman, “Comparison of test methods to assess pozzolanic activity,” *Cem. Concr. Compos.*, vol. 32, no. 2, pp. 121–127, Feb. 2010, doi: 10.1016/j.cemconcomp.2009.10.008.

[27] A. R. Pourkhorshidi, M. Najimi, T. Parhizkar, F. Jafarpour, and B. Hillemeier, “Applicability of the standard specifications of ASTM C618 for evaluation of natural pozzolans,” *Cem. Concr. Compos.*, vol. 32, no. 10, pp. 794–800, Nov. 2010, doi: 10.1016/j.cemconcomp.2010.08.007.

[28] A. C150/C150M-22, “Standard Specification for Portland Cement.”

[29] ACI Committee 232, “232.2R-18: Report for the Use of Fly Ash in Concrete,” 2018.

[30] ACI Committee 232, *ACI 232.1R-12 Report on the Use of Raw or Processed Natural Pozzolans in Concrete*. 2012.

[31] ACI Committee 233, *ACI 233R-17 Guide to the Use of Slag Cement in Concrete and Mortar*. 2017.

[32] ACI Committee 234, *ACI 234R-06 Guide for the Use of Silica Fume in Concrete*. American Concrete Institute, 2012.

[33] M. Kasaniya, M. D. A. Thomas, and E. G. Moffatt, “Pozzolanic reactivity of natural pozzolans, ground glasses and coal bottom ashes and implication of their incorporation on the chloride permeability of concrete,” *Cem. Concr. Res.*, vol. 139, p. 106259, Jan. 2021, doi: 10.1016/j.cemconres.2020.106259.

[34] S. Seraj and M. Juenger, “Evaluation of an accelerated characterization method for pozzolanic reactivity,” *ACI Spec. Publ.*, vol. 312, 2016.

[35] J. Tanesi, L. Montanari, and A. Ardani, “Formation Factor Demystified and its Relationship to Durability.” FHWA, McLean, VA, 2019. doi: FHWA-HRT-19-044.

[36] Y. Wang, L. Burris, C. R. Shearer, D. Hooton, and P. Suraneni, “Strength activity index and bulk resistivity index modifications that differentiate inert and reactive materials,” *Cem. Concr. Compos.*, vol. 124, p. 104240, Nov. 2021, doi: 10.1016/j.cemconcomp.2021.104240.

[37] J. Chapelle, “Attaque sulfocalcique des laitiers et pouzzolanes,” *Rev. des Matériaux Constr.*, vol. 512, pp. 136–145, 1958.

[38] J. Forest and E. Demoulian, “Appréciation de l’activité des Cendres Volantes et Pouzzolanes,” *Rev. des Matériaux Constr.*, vol. 577, pp. 312–317, 1963.

[39] J. D. Watt and D. J. Thorne, “The composition and pozzolanic properties of pulverised fuel ashes,” *J. Appl. Chem.*, vol. 15, pp. 585–604, May 1965, doi: 10.1002/jctb.5010160201.

[40] U. Costa and F. Massazza, “Factors affecting the reaction with lime of Italian pozzolanas,” *Cem. 3*, pp. 131–139, 1974.

[41] F. Massazza, “Chemistry of Pozzolanic Additions and Mixed Cements,” in *6th ICCC*, 1974.

[42] R. Snellings and K. Scrivener, “The (Hi) Story of a Generic Reactivity Test for Supplementary Cementitious Materials,” 2018.

[43] X. Li *et al.*, “Reactivity tests for supplementary cementitious materials: RILEM TC 267-TRM phase 1,” *Mater. Struct.*, vol. 51, no. 6, p. 151, Dec. 2018, doi: 10.1617/s11527-018-1269-x.

[44] R. Snellings, X. Li, F. Avet, and K. Scrivener, “A Rapid, Robust, and Relevant (R3) Reactivity Test for Supplementary Cementitious Materials,” *ACI Mater. J.*, vol. 116, no. 4, Jul. 2019, doi: 10.14359/51716719.

[45] ASTM C1897-20, “Standard Test Methods for Measuring the Reactivity of Supplementary Cementitious Materials by Isothermal Calorimetry and Bound Water Measurements.” ASTM International, West Conshohocken, PA, 2020.

[46] ASTM C1738/C1738M-19, “Standard Practice for High-Shear Mixing of Hydraulic Cement Pastes.” American Association of State Highway and Transportation Officers, 2019.

[47] Y. Wang, S. Ramanathan, L. Burris, R. D. Hooton, C. R. Shearer, and P. Suraneni, “Reactivity of Unconventional Fly Ashes, SCMs, and Fillers: Effects of Sulfates, Carbonates, and Temperature,” *Adv. Civ. Eng. Mater.*, vol. 11, no. 2, p. 20220003, Feb. 2022, doi: 10.1520/ACEM20220003.

[48] S. Ramanathan, L. R. Pestana, and P. Suraneni, “Reaction kinetics of supplementary cementitious materials in reactivity tests,” *Cement*, vol. 8, p. 100022, Jun. 2022, doi: 10.1016/j.cement.2022.100022.

[49] P. Suraneni, A. Hajibabaee, S. Ramanathan, Y. Wang, and J. Weiss, “New insights from reactivity testing of supplementary cementitious materials,” *Cem. Concr. Compos.*, vol. 103, pp. 331–338, Oct. 2019, doi: 10.1016/j.cemconcomp.2019.05.017.

[50] D. Londono-Zuluaga *et al.*, “Report of RILEM TC 267-TRM phase 3: validation of the R3 reactivity test across a wide range of materials,” *Mater. Struct.*, vol. 55, no. 5, p. 142, Jun. 2022, doi: 10.1617/s11527-022-01947-3.

[51] G. C. Anzalone, I. Diaz-Loya, R. Y. Minkara, and L. L. Sutter, “Comparison of Methods to Measure Adsorptive Capacity of Coal Fly Ash,” *ACI Mater. J.*, vol. 116, no. 4, Jul. 2019, doi:

10.14359/51716715.

[52] S. Tritsch, L. Sutter, and I. Diaz-Loya, “TechBrief - Use of Harvested Fly Ash in Highway Infrastructure.” National Concrete Pavement Technology Center, p. 11, 2021.

[53] L. Sutter, D. Hooton, and S. Schlorholtz, “Methods for Evaluating Fly Ash for Use in Highway Concrete, NCHRP Report 749,” Washington, D.C., 2013.

[54] A. Ardani, H. Kim, and M. Nicolaescu, “Fly Ash AEA Adsorption Capacity Estimation as Measured by Fluorescence or Foam Index,” *FHWA-HRT-17-118*, p. 15, 2017.

[55] R. Meininger, “Use of Fly Ash in Concrete,” *Report of Recent NSGA-NRMCA Research Laboratory Studies, Series J 153. Technical Information Letter No. 381, National Ready-Mixed Concrete Association*, 1981.

[56] S. Gebler and P. Klieger, “Effect of Fly Ash on the Air-Void Stability of Concrete,” *Concr. ACI Concr. Symp.*, vol. SP 79, pp. 103–142, 1983, doi: 10.14359/6688.

[57] V. H. Dodson, *Concrete Admixtures*. Boston, MA: Springer US, 1990. doi: 10.1007/978-1-4757-4843-7.

[58] E. Freeman, Y.-M. Gao, R. Hurt, and E. Suuberg, “Interactions of carbon-containing fly ash with commercial air-entraining admixtures for concrete,” *Fuel*, vol. 76, no. 8, pp. 761–765, Jun. 1997, doi: 10.1016/S0016-2361(96)00193-7.

[59] J. P. Baltrus and R. B. LaCount, “Measurement of adsorption of air-entraining admixture on fly ash in concrete and cement,” *Cem. Concr. Res.*, vol. 31, no. 5, pp. 819–824, May 2001, doi: 10.1016/S0008-8846(01)00494-X.

[60] I. Külaots, A. Hsu, R. H. Hurt, and E. M. Suuberg, “Adsorption of surfactants on unburned carbon in fly ash and development of a standardized foam index test,” *Cem. Concr. Res.*, vol. 33, no. 12, pp. 2091–2099, Dec. 2003, doi: 10.1016/S0008-8846(03)00232-1.

[61] ASTM C1827-20, “Standard Test Method for Determination of the Air-Entraining Admixture Demand of a Cementitious,” West Conshohocken, PA, 2020.

[62] T. . Gurupira, M. . Ochsenbein, J. M. . Stencel, and F. Martinus, “Development of an Automated Foam Index Test,” in *World of Coal Ash*, 2005.

[63] P. Taylor, V. . Johansen, A. . Graf, R. . Kozikowski, J. Zemajtis, and C. Ferraris, “Identifying Incompatible Combinations of Concrete Materials: Volume II—Test Protocol. Publication No. FHWA-HRT-06-080.” 2006.

[64] J. M. Stencel, H. Song, and F. Cangialosi, “Automated foam index test: Quantifying air entraining agent addition and interactions with fly ash–cement admixtures,” *Cem. Concr. Res.*, vol. 39, no. 4, pp. 362–370, Apr. 2009, doi: 10.1016/j.cemconres.2009.01.010.

[65] S. Jacobsen, H. Nordahl-Pedersen, H. Rasol, and O. Lødemel, “Foam Index measurements on combinations of Air Entraining Agents, Superplasticicers and Fly ash/cement/filler powder mixes,” 2015.

[66] N. J. Harris, K. C. Hover, K. J. Folliard, and M. T. Ley, “The Use of the Foam Index Test to Predict AEA Dosage in Concrete Containing Fly Ash: Part I—Evaluation of the State of Practice,” *J. ASTM Int.*, vol. 5, no. 7, p. 101601, 2008, doi: 10.1520/JAI101601.

[67] ASTM C125-21a, “Standard Terminology Relating to Concrete and Concrete Aggregates.” American

Association of State Highway and Transportation Officers, 2021.

[68] ASTM C604-18(2023), “Standard Test Method for True Specific Gravity of Refractory Materials by Gas-Comparison Pycnometer.”

[69] ASTM C204-24, “Standard Test Methods for Fineness of Hydraulic Cement by Air-Permeability Apparatus.” ASTM International, 2024.

[70] ASTM C191-21, “Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle.” American Association of State Highway and Transportation Officers, 2021.

[71] ASTM C1437-20, “Standard Test Method for Flow of Hydraulic Cement Mortar.” ASTM International, 2020.

[72] ACI Committee 211, “ACI PRC-211.1-22: Selecting Proportions for Normal-Density and High Density-Concrete - Guide,” 2022. doi: 9781641951869.

[73] ASTM C192/C192M-19, “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory.” 2019. doi: 10.1520/C0192_C0192M-19.

[74] AASHTO R 39-19, “Standard Method of Test for Making and Curing Concrete Test Specimens in the Field.” American Association of State Highway and Transportation Officials, Washington, D.C., pp. 1–14, 2020.

[75] AASHTO T 119M/119-23, “Standard Method of Test for Slump of Hydraulic Cement Concrete.” American Association of State Highway and Transportation Officials, Washington, D.C., 2023.

[76] AASHTO T 396-22, “Standard Method of Evaluating the Workability of Slip Form Concrete Paving with the Box Test.” 2022.

[77] AASHTO T 121M/T 121-23, “Standard Method of Test for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete.” American Association of State Highway and Transportation Officials, Washington, D.C., 2023.

[78] AASHTO T 395-22, “Standard Method of Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method.” American Association of State Highway and Transportation Officers, 2022.

[79] AASHTO T 197M/T 197-23, “Standard Method of Test for Time of Setting of Concrete Mixtures by Penetration Resistance.” American Association of State Highway and Transportation Officers, 2023.

[80] AASHTO T 365-20, “Standard Method of Test for Quantifying Calcium Oxychloride Formation Potential of Cementitious Pastes Exposed to Deicing Salts,” *Am. Assoc. State Highw. Transp. Off.*, 2020.

[81] H. Abdi and L. Williams, *The SAGE encyclopedia of research design*. Thousand Oaks: Sage Publications, 2021.

[82] AASHTO T 22M/T22-22, “Standard Method of Test for Compressive Strength of Cylindrical Concrete Specimens.” American Association of State Highway and Transportation Officials, Washington, D.C., 2022.

[83] AASHTO T 97M/T 97-23, “Standard Method of Test for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading).” American Association of State Highway and Transportation Officials, Washington, D.C., 2023.

[84] ASTM C157/C127M-17, “Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete,” *Am. Soc. Test. Mater.*, 2017.

[85] AASHTO T 161-22, “Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing.” American Association of State Highway and Transportation Officers, Washington D.C., 2022.

[86] AASHTO T 358-22, “Standard Method of Test for Surface Resistivity Indication of Concrete’s Ability to Resist Chloride Ion Penetration.” American Association of State Highway and Transportation Officials, Washington, D.C., 2022.

[87] R. Snellings, G. Mertens, and J. Elsen, “Supplementary Cementitious Materials,” *Rev. Mineral. Geochemistry*, vol. 74, no. 1, pp. 211–278, Jan. 2012, doi: 10.2138/rmg.2012.74.6.

[88] L. Barcelo, M. D. A. Thomas, K. Cail, A. Delagrave, and B. Blair, “Portland Limestone Cement Equivalent Strength Explained,” *Concr. Int.*, vol. November, pp. 41–47, 2013.

[89] K. E. Kurtis, L. Kahn, A. Shalan, B. Zaribaf, and E. Nadelman, “Assessment of Limestone Blended Cement for Transportation Applications, FHWA-GA-17-13-09,” Drive Forest Park, 2017.

[90] C. Qiao, P. Suraneni, M. Tsui Chang, and J. Weiss, “Damage in cement pastes exposed to MgCl2 solutions,” *Mater. Struct.*, vol. 51, no. 3, p. 74, Jun. 2018, doi: 10.1617/s11527-018-1191-2.

[91] P. Suraneni, V. Azad, O. B. Isgor, and J. Weiss, “Deicing Salts and Durability of Concrete pavements and Joints: Mitigating Calcium Oxychloride Formation,” *Concete Int.*, vol. 38, no. 4, pp. 48–54, 2016.

[92] L. Montanari, J. Tanesi, H. Kim, and A. Ardani, “Quantification of Calcium Oxychloride by Differential Scanning Calorimetry: Validation and Optimization of the Testing Procedure,” *Adv. Civ. Eng. Mater.*, vol. 10, no. 1, p. 20200122, Jun. 2021, doi: 10.1520/ACEM20200122.

[93] AASHTO R 101-22, “Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures.” 2022.

[94] Y. Farnam, B. Zhang, and J. Weiss, “Evaluating the use of supplementary cementitious materials to mitigate damage in cementitious materials exposed to calcium chloride deicing salt,” *Cem. Concr. Compos.*, vol. 81, pp. 77–86, Aug. 2017, doi: 10.1016/j.cemconcomp.2017.05.003.

[95] M. D. A. Thomas, R. D. Hooton, A. Scott, and H. Zibara, “The effect of supplementary cementitious materials on chloride binding in hardened cement paste,” *Cem. Concr. Res.*, vol. 42, no. 1, pp. 1–7, Jan. 2012, doi: 10.1016/j.cemconres.2011.01.001.

[96] H. Hall *et al.*, “Improving Specifications to Resist Frost Damage in Modern Concrete Mixtures, Pool Fund Study TPF-5-297,” 2019.

[97] J. Tanesi, H. Kim, M. Beyene, and A. Ardani, “Super Air Meter for Assessing Air-Void System of Fresh Concrete,” *Adv. Civ. Eng. Mater.*, vol. 5, no. 2, p. 20150009, Dec. 2016, doi: 10.1520/ACEM20150009.

[98] ACI Committee 201, “Guide to Durable Concrete,” 2016.

[99] Wisconsin Department of Transportation, “WTM T358, Manual of Test Procedures.” Wisconsin Department of Transportation, Bureau of Project Development, Madison, p. 168, 2024.

[100] J. Payá, J. Monzó, M. . Borrachero, E. Perris, and F. Amahjour, “Thermogravimetric Methods for Determining Carbon Content in Fly Ashes,” *Cem. Concr. Res.*, vol. 28, no. 5, pp. 675–686, May 1998, doi: 10.1016/S0008-8846(98)00030-1.

[101] Y. Wang, B. C. Acarturk, L. Burris, R. D. Hooton, C. R. Shearer, and P. Suraneni, “Physicochemical characterization of unconventional fly ashes,” *Fuel*, vol. 316, p. 123318, May 2022, doi: 10.1016/j.fuel.2022.123318.

[102] D. P. Bentz *et al.*, “Influence of aggregate characteristics on concrete performance,” Gaithersburg, MD, May 2017. doi: 10.6028/NIST.TN.1963.

[103] J. Tanesi, A. A. Ardani, and J. C. Leavitt, “Reducing the Specimen Size of the AASHTO T 97 Concrete Flexural Strength Test for Safety and Ease of Handling,” *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2342, no. 1, pp. 99–105, Jan. 2013, doi: 10.3141/2342-12.

APPENDIX A

This appendix presents the industry and government perspective regarding the use of new materials and alternative supplementary cementitious materials. The following individuals were contacted. Their perspectives are summarized below.

	State	Name
State DOTs	Wisconsin	Dante Fratta
		Jim Parry – retired in summer 2023
	Illinois	James Krstulovich
	Indiana	Mike Nelson
	Iowa	Todd Hanson
	Michigan	Thomas Bahmer Tim Stallard
	Missouri	Brett Trautman
	MnDOT	Maria Masten Rob Golish
	Nebraska	Lieska Halsey Wally Heyen
	Ohio	Mohamed Salim Jordan Zamary Prasad Kudlapur Marcos Olivares
Federal	Wisconsin FHWA	James Pfoor
	Michigan FHWA	Adnan Iftikhar
	Missouri FHWA	Mike McGee
Other Agencies	Illinois Tollway	Ross Bensten and Dan Gancarz
	USACE	Robert Moser
Industry	3M	John Edwards
	Ashcor	Saiprasad Vaidya
	EcoMaterials	Andy Glass, Doug Rhodes, Craig Wallace
	Liquid Fly Ash	Kevin Moore, Ben Shetterley
	Michigan Concrete Association	Dan De Graaf
	National Minerals Corporation – Bottom Ash	Travis Collins
	Ramboll	Marina Kozhukhova
	Votorantin Cement	Nick Popoff
	WRMCA	Cherish Schwenn

Main Obstacles for Use or Implementation of New Materials:

- Lack of experience and historical data on performance
- Unknown durability

- Lack of adequate testing procedures or guides to evaluate such materials
- Equipment, difficulty and repeatability of tests
- Uniformity and consistency of the material
- Lack of reliable available sources
- DOTs culture and mindset encourages status quo
- Feds need to take a stand on using materials that do not comply with standards or don't have standards yet
- Need to convince contractors and regional engineers to try new materials
- Materials may require more training, especially how to address unexpected behavior or issues

Specific Issues for WisDOT:

- The struggle with implementing any new SCM's is that the state does not easily allow the use of any new products unless it is on the approved product list or there has been a lot of testing performed using these products,
- WisDOT requires special testing even for Class F fly ash that has historical data. These tests cost $100 k and producers cannot justify this cost,
- Fly ashes are required to have a very low LOI,
- WisDOT leans on the cement and fly ash producers to also produce feasible/ practical/ economical products in place of fly ash,
- Need to switch from Prescriptive Mix Designs to Performance Mix Designs,
- In Wisconsin, ready mixed concrete plants have 3-4 silos. Because of the cement shortage, 2-3 silos are used for cement. Any new material will require extensive investments to add silos,
- No investment will be made until WisDOT has approved the materials,
- Concrete producers want to use slag and NP100 but they can't justify the testing expenses right now,
- Lack of communication between all parties concerned in Wisconsin.

APPENDIX B

Following is a summary of the specifications of some State DOTs.

State	Cementitious	Total SCM	Fly Ash	Slag	High Reactivity Pozzolan	Blended SCM	Notes
CDOT	Min. 520 pcy	Max 50%	F – max 30% C – max 20%	Max 50%	AASHTO M321 Max 30% (Include natural pozzolans)	Not in spec. Not aware of memo	Different max % replacement for C1157 cement
IOWA DOT SMARTER I SIMPLER I CUSTOMER DRIVEN	-	Max 50%	Max 20% Replace F with C	Max 35%	-	Max 20%	-
Illinois Department of Transportation	Min. 565 pcy Max 705 pcy		F – max 25% C – max 30%	Max 35%	Microsilica or Metakaolin – max 10%	Memo	Blended SCM: only final product comply with predominant material spec.
INDIANA DEPARTMENT OF TRANSPORTATION INDOT	Min. 450 pcy Max 752 pcy Cement min. 275 pcy	Min. 25% Max 40%	Max 30%	Max 30%	-	-	Shall not contain more than 2 SCMs
MI	470-564 pcy	Min. 25% Max 40% for HP	Allowed				
mn DEPARTMENT OF TRANSPORTATION	Min. 475 pcy Max 615 pcy Cement: min. 385 pcy	Max 40% for ternary blends	Max 25% For ASR up 33%	Max 35%	-	Yes	-
MoDOT	Min. 560 pcy	Max 40% for ternary blends	Max 25%	Max 25% (Type IS)	-	Yes	-

State	Cementitious	Total SCM	Fly Ash	Slag	High Reactivity Pozzolan	Blended SCM	Notes
ND TRANSPORTATION	550-650 pcy	Max 35%	-	-	-	-	-
NEBRASKA Good Life. Great Journey. DEPARTMENT OF TRANSPORTATION	Min. 564 pcy	Max 40%	Max 25% (Class F/Type IP)	Max 35% (Type IS)	-	Yes	-
NJ	Min. 564 pcy	-	Max 25% (Type IP)	Max 50%	-	-	-
OH	Min. 520 pcy	Max 50%	Max 25%	Max 30%	-	-	-
SD DOT	Min. 600 pcy	-	Min. 15% Max 25%	-	-	-	-
UDOT Keeping Utah Moving	-	Max 30%	Max 30%	-	-	-	-
WY	Min. 564 pcy Max 705 pcy Cement min 470 pcy (with FA)	-	20-25%	20-50%	-	-	-
FEDERAL AVIATION ADMINISTRATION	Min. 470 pcy Max 517 pcy	-	Min. 20% Max 30% With slag, max 10%	Min. 25% Max 55%	-	-	**Natural P.** Min. 20% Max 30% With slag, max 10%

State/ Agency	Cementitious	Total SCM	Fly Ash	Slag	High Reactivity Pozzolan	Blended SCM	Notes
DEPARTMENT OF TRANSPORTATION UNITED STATES OF AMERICA	-	Max 50 % (slag) or Max 35%	Max. 25%	Max 50%	-	-	-

Note: When class F or class C are not specifically mentioned, it means that the max applies to either of them.

APPENDIX C

In this appendix, the factors affecting the results of the foam index are presented.

Standard Solution Concentration and Type of AEA

The concentration of the AEA standard solution concentration plays a major role on the time and AEA demand to form the a stable foam, as well as on the accuracy and reproducibility of the test, because using a relatively low concentration solution with a highly adsorbent CFA requires numerous additions of AEA, increasing human error and lengthening the testing time [67]. The different chemistry of AEA types also plays a role in the AEA demand. Table 1 shows a comparison of different versions of the foam index test in terms of concentrations, addition rates and type of AEA.

Cement

Several studies have reported the influence of cement chemistry on the AEA demand. For example, cements with higher alkali contents reduce air loss and decrease AEA demand [56], [59], [60]. Similarly, the SO_3 content also decreases the AEA requirements [56]. Additionally, Kulaots *et al*. [60] noticed that finely divided calcium solids in the cement are important for stabilization of the foam.

Table 1 – Standard Solution Concentration, Addition Rates and Type of AEA in Different Versions of Foam Index

	AEA Dilution	AEA Addition per Cycle	AEA
Meininger, 1981 [55]	1:20	NS[1]	Any
Freeman, 1997 [58]	1:10	1 to 5 drops at a time	Daravair 1000, Darex II
Baltrus, 2001 [59]	1:40	0.05 mL	Darex II
Külaots, 2003 [60]	1:10	0.01 mL minimum	Any
ASTM C1827 [61]	Suggestion: 1:40, 1:20, 1:12.5, 1:10, 1:6.5	1 drop	Any
ASTM C1827, MnDOT Modified (Tyler Ley)	1:40	2 to 5 drops	Wood rosin or Vinsol resin
FHWA - Taylor et al., 2006 [63]	Any	NS[1]	Any
Harris, 2008 [66], [68], [69]	1:20	-	Vinsol resin
Sutter et al., 2012 [53]	NS[1]	1 drop	Any
Jacobsen, 2015 [65]	1:10	-	Any

[1] NS: Not specified.

Shaking Procedure

The shaking procedure can be manual or mechanical. The manual procedure will result in a variable agitation from operator to operator, while the mechanical procedure will maintain the agitation constant [1].

Additionally, some other factors that affect the energy applied during the shaking period, and may differ from version to version, are the agitation displacement of the container from a starting point and back, the agitation rate and the agitation duration. It has been shown that the more energy applied during the shaking process, the lower the foam index, i.e., a lower dose of AEA is needed to stabilize the foam [69]. Table 2 shows a summary of shaking procedures used in different versions of the foam index test.

Table 2 – Comparison of Different Shaking Procedures

	Type of agitation	Agitation Rate, shakes/s	Shake Displacement, mm	Agitation time, s
Meininger, 1981 [55]	Manual	NS[1]	NS[1]	15
Freeman, 1997 [58]	Manual	NS[1]	NS[1]	15
Baltrus, 2001 [59]	Manual	NS[1]	NS[1]	15
Külaots, 2003 [60]	Manual	NS[1]	NS[1]	15
ASTM C1827 [61]	Mechanical or Manual	4 ± 0.5	225 ± 25	10 ± 0.5
ASTM C1827, MnDOT Modified (Tyler Ley)	Manual	2	225	20
FHWA - Taylor et al., 2006 [63]	Manual	NS[1]	NS[1]	15
Harris, 2008 [66], [68], [69]	Manual	3 to 5 Hz	Vertical 200 to 250	10
Sutter et al., 2012 [53]	Mechanical	NS[1]	200	10
Jacobsen, 2015 [65]	Mechanical	10 Hz	200	15
[1] NS: Not specified.				

Container Geometry in Relation to Sample Size

When using manual shaking, one aspect that is very important is that the container fits in the operator's hand. As a result, different versions of the test require different container size (Table 3).

However, another aspect that sometimes is overlooked is the ratio between the volume of the slurry and the volume of the container. Table 5 shows how this ratio varies from one version of the test to another. Harris et al. investigated this aspect [69]. They observed that when a stable foam is formed (end of the test), the thickness of the foam was typically 4-5 mm, regardless of the surface area of the liquid-air interface (diameter of container). Moreover, they determined that for a given container diameter, and foam layer thickness at the end of the test, the greater the fill ratio, the lower the AEA dosage needed to create a stable foam layer, because the foam layer will represent a smaller portion of the slurry[69] (Figure 1).

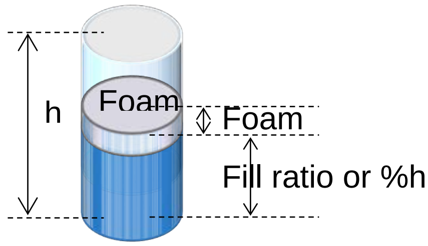


Figure 1 – Ratio between foam layer and container height [69].

Table 3 – Comparison of the Geometry and Slurry Volume of Different Versions of Foam Index

	Container, mL	Slurry/container vol, %	Water vol, mL	Cement, g	Fly Ash, g
Meininger, 1981 [55]	120	12	50	16	4
Freeman, 1997 [58]	350	8	25	8	2
Baltrus, 2001 [59]	15	39	5	-	2
Külaots, 2003 [60]	70	40	25	8	2
ASTM C1827 [61]	250	11.3	25 ± 1	8.00 ± 0.05	2.00 ± 0.05
ASTM C1827, MnDOT Modified (Tyler Ley)	125	22.9	25	5	5
FHWA - Taylor et al., 2006 [63]	500	11.3	50	16	4
Harris, 2008 [66], [68], [69]	200	20	25	8	2
Sutter et al., 2012 [53]	250	11.3	25	8	2
Jacobsen, 2015 [65]	70	40	25	8	2

Foam Index

ASTM C 1827 MnDOT Modified - Tyler Ley Procedure

Summary of Changes

The existing foam index procedure for the foam index is modified to make the procedure more specific. These modifications have been shown in laboratory testing to reduce the variability of the test and better correlate with the performance of the CCA in a concrete mixture. The changes made include a more specific mixing container, a more specific dropper, a different CCA to fly ash ratio, a more specific concentration and type of air entraining solution, and a different rate of shaking. All changes are made based on previous publications and laboratory testing. Each modification of ASTM C 1827 is summarized by section.

Apparatus

Use a 125 mL plastic container with a diameter of 63 mm (2.5") and a tight-fitting silicone lid. Examples are:

- Nalgene Tritan Jar - 4oz
- Silicone lid (2.6" diameter)
- Use a pipette to deliver drops that are < 45 µL as determined by ASTM C1827. An example of this is a Flents Straight & Bent Tip Medicine Droppers, 1ml Capacity.

Materials

Use a 2.5% concentration of wood rosin or Vinsol resin AEA. Examples include MBVR from Master Builders, AE 90 from Master Builders, and Daravair 1000 or an approved equivalent.

Procedure

Use a slurry of 5g of cement, 5g of CCA, and 25mL of water.

The 2.5% AEA concentration can be added at two to five drops at a time.

Shake the container for twenty seconds at a rate of 2 shakes/second, where a single shake is done by manually holding the container at arm's length and only grasping the silicone lid of the container so that the operator's hand does not increase the temperature of the slurry. A shake is considered a displacement of 225 +/- 25 mm.

After twenty seconds of shaking, the container is placed on a flat surface and the lid is immediately removed. The container should sit undisturbed for 20 s +/- 1 s and then the foam surface should be visually inspected.

If the slurry does not contain a foam that completely covers the surface at the end of the rest period, then more drops are added, and the material is shaken for 10 +/- 1 seconds. This process is repeated until a foam completely covers the surface at the end of the rest period. This is called a stable foam. Figure 2 shows a comparison of the surface of the container at the beginning and end of a test. The number of drops to reach this is used in calculating the Foam Index value.

The results of the test are expressed in the number of drops that are converted to the volume of diluted AEA and this is divided by the amount of cement and CCA in the slurry. The volume of a drop is determined as outlined in ASTM C1827.

Unstable Foam Stable Foam

Figure 2 – Examples of unstable and stable foam on the surface of the container.

Calculations

Since the concentration of AEA is fixed at 2.5% and the amount of cement and fly ash are fixed. The final results are expressed in µL of AEA/ g of cementitious material. This can be calculated with the following equation and variables:

Foam Index Value = DV(A/100)/cm

D = Number of drops

V = volume of the drop in microliters per drop. This is determined for each pipette as outlined in ASTM C 1827.

A = concentration of AEA in percentage. For this work, it is 2.5% and so this is taken at 2.5.

cm = grams of cementitious material. For this work, it is 10 g.

Precision and Bias

The average standard deviation is 0.08 µL AEA/g of cm for the MnDOT modified version of the test method based on a single operator in a single laboratory. This was completed with a wide range of CCAs with foam index values between 1 and 4.3 µL AEA/g of cm and three replicates per test. This means that a test would not be expected to vary by more than 0.16 µL AEA/g of cm with a 95% confidence interval. Multi laboratory testing is underway.

APPENDIX D

Modified SAI procedure

Follow the ASTM C311/C311M procedure with the exception of:

Control Mixture

- 740 g of hydraulic cement
- 2035 g of graded standard sand
- 362.6 g of water
- Calculate the volume of cementitious: Vcc

Test Mixture

- 518 g of hydraulic cement
- 222 g of SCM (30% of cement replacement by mass)
- Calculate total volume of cementitious: Vctest
- 362.6 g of water
- Subtract the volume of the cement of the control mixture from the volume of cementitious materials from the test mixture. This is Ve.
- Convert the volume of sand of the control mixture to mass of sand – Vsc
- Subtract Ve from Vsc and convert the result to mass.

Example:

Cement specific gravity: 3.15 g/cm^3.

Sand specific gravity: 2.65 g/cm^3.

Fly ash specific gravity: 2.58 g/cm^3.

- Control mixture Vcc = 740/3.15 = 234.92 cm^3.
- Test mixture Vctest = 518/3.15 + 222/2.58 = 164.44 + 86.05 = 250.49 cm^3.
- Vctest – Vcc = Ve =15.57 cm^3.
- Sand volume of control mixture Vsc: 2035/2.65 = 767.92 cm^3.
- Subtract Ve from Vsc = 767.92- 15.57 = 752.35 cm^3 = Vstest
- Convert the volume of sand of the test mixture to mass = 752.35 * 2.65 = 1,993.74 g.

Test mixture: 518 g of hydraulic cement, 222g of fly ash, 1,993.74 g of sand and 362.6 g of water.

APPENDIX E

Appendix E presents the test results.

Setting Time

The setting behavior of the pastes can be found in Figure 2 and Figure 3.

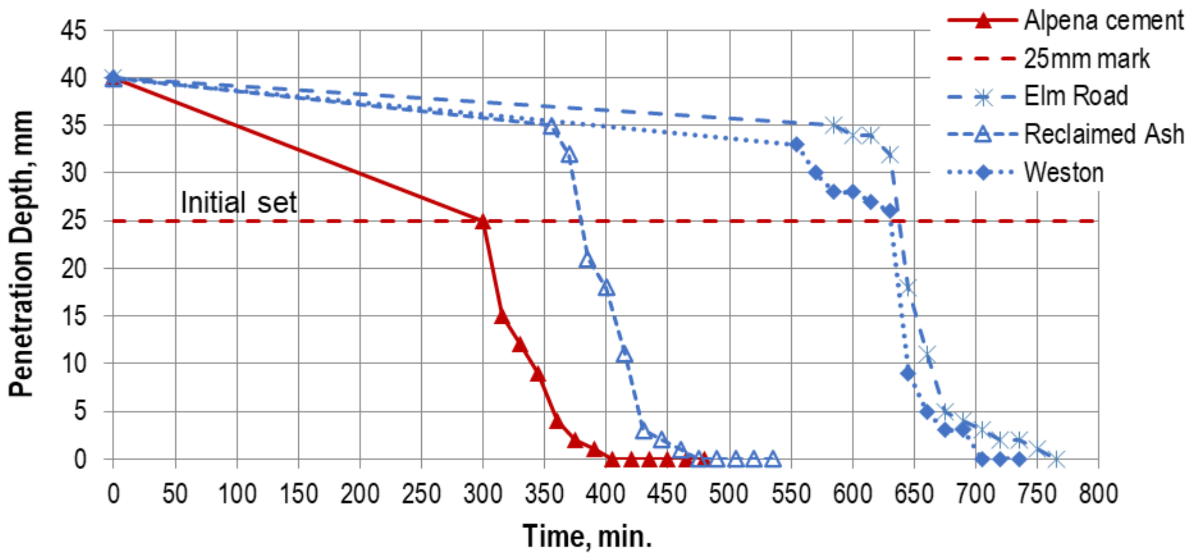


Figure 3 – Setting time of cement and Class C fly ashes.

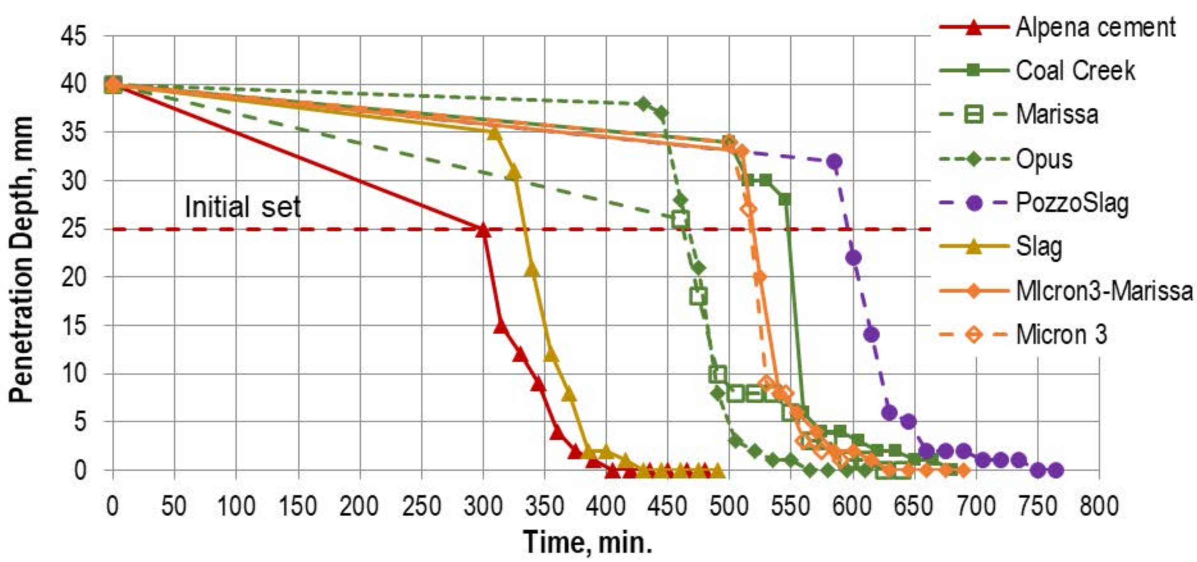
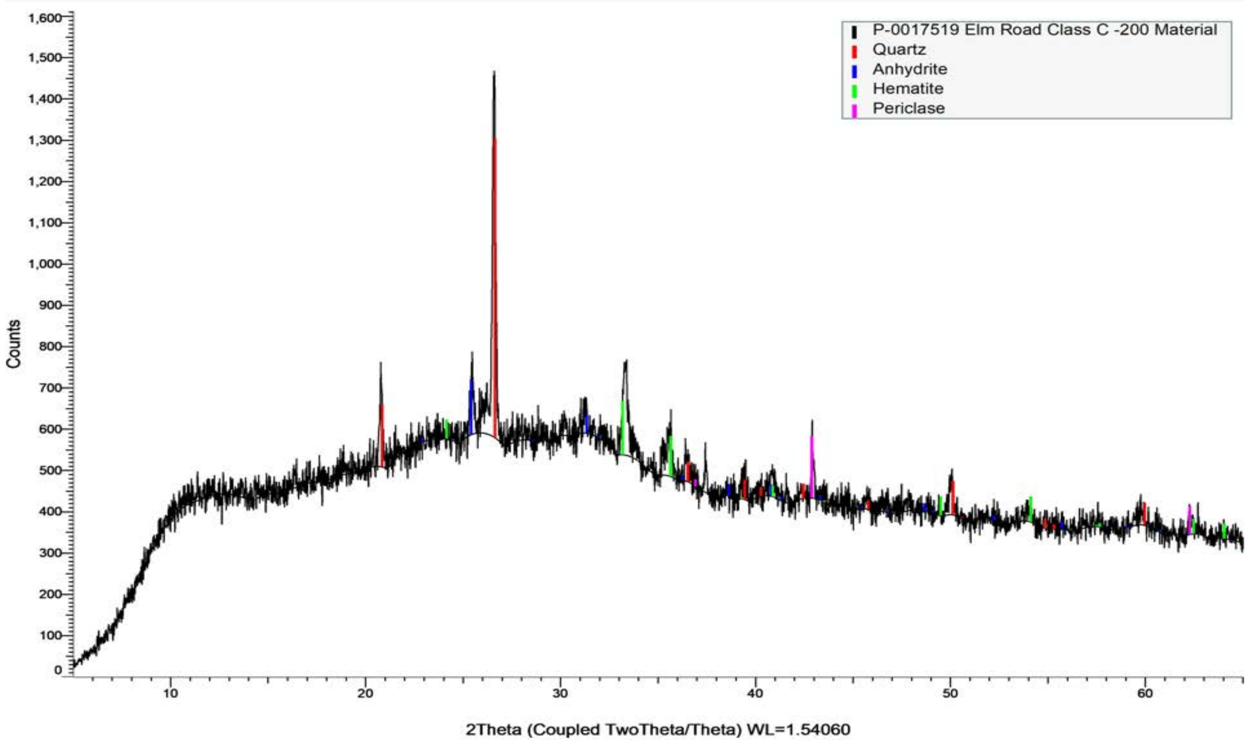


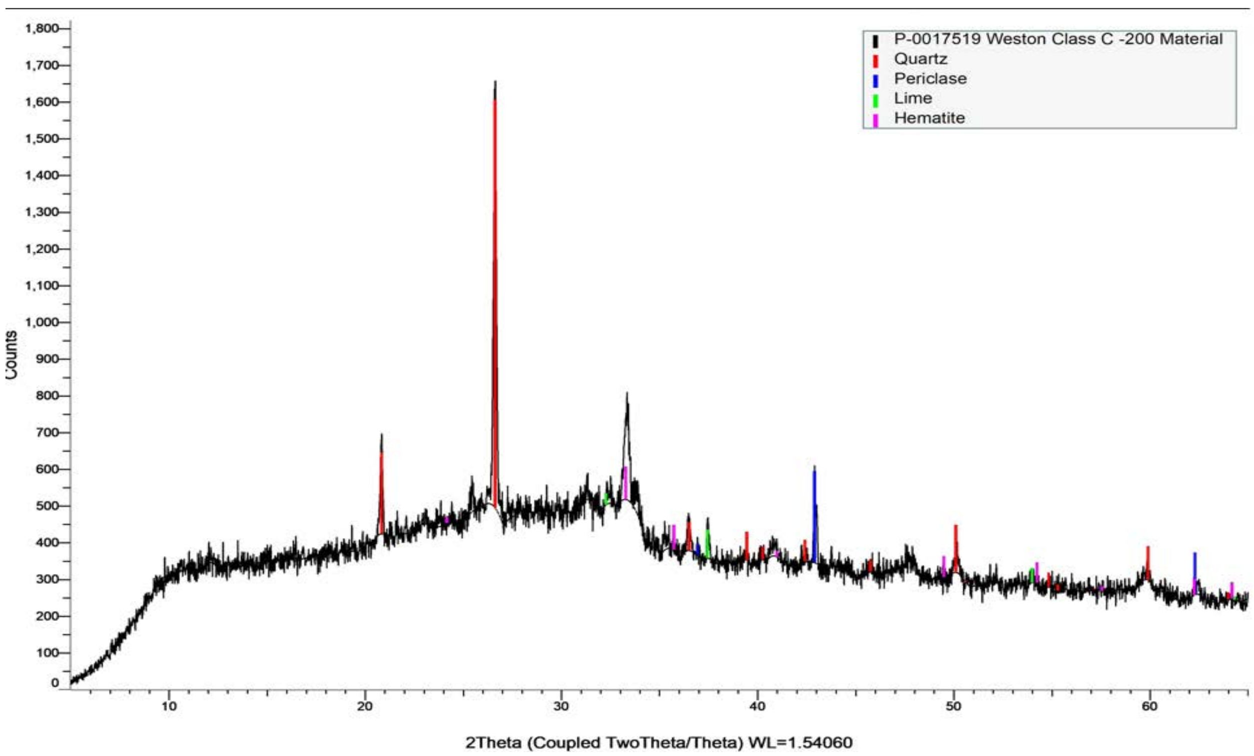
Figure 4 – Setting time of cement, marketed as Class F fly ashes, and slag.

XRD diffractograms

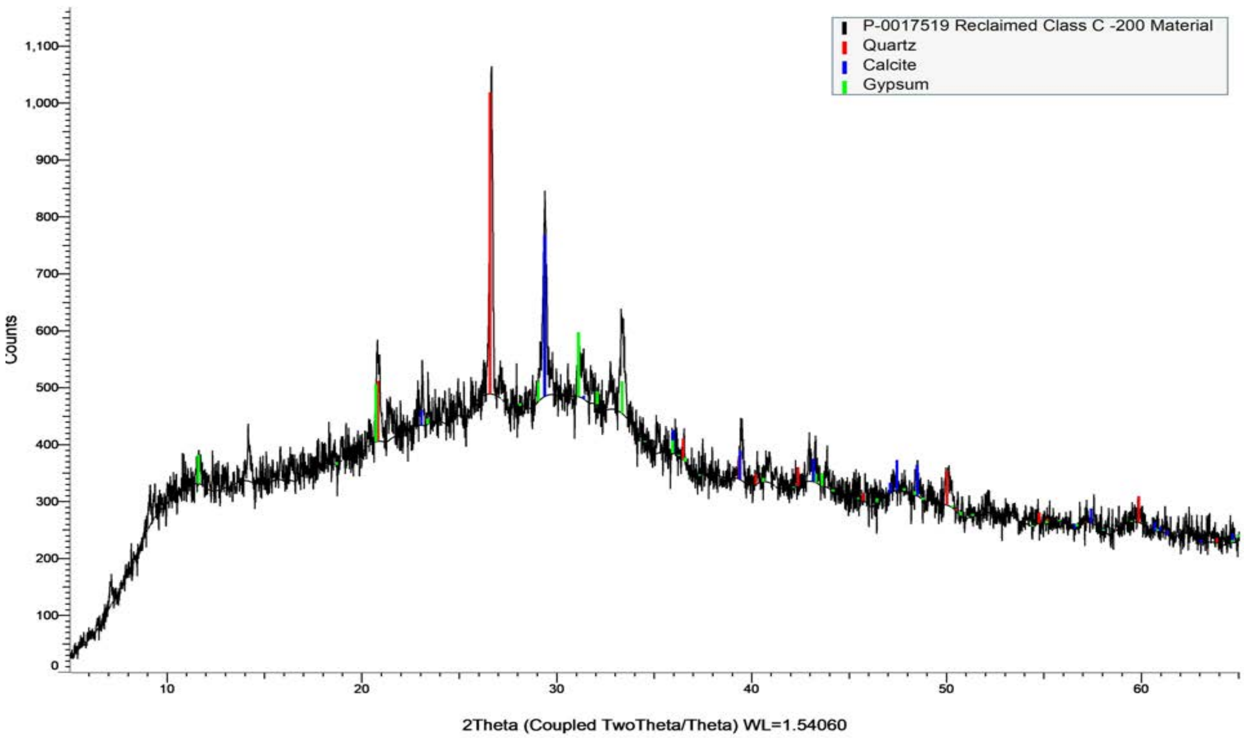
Elm Road



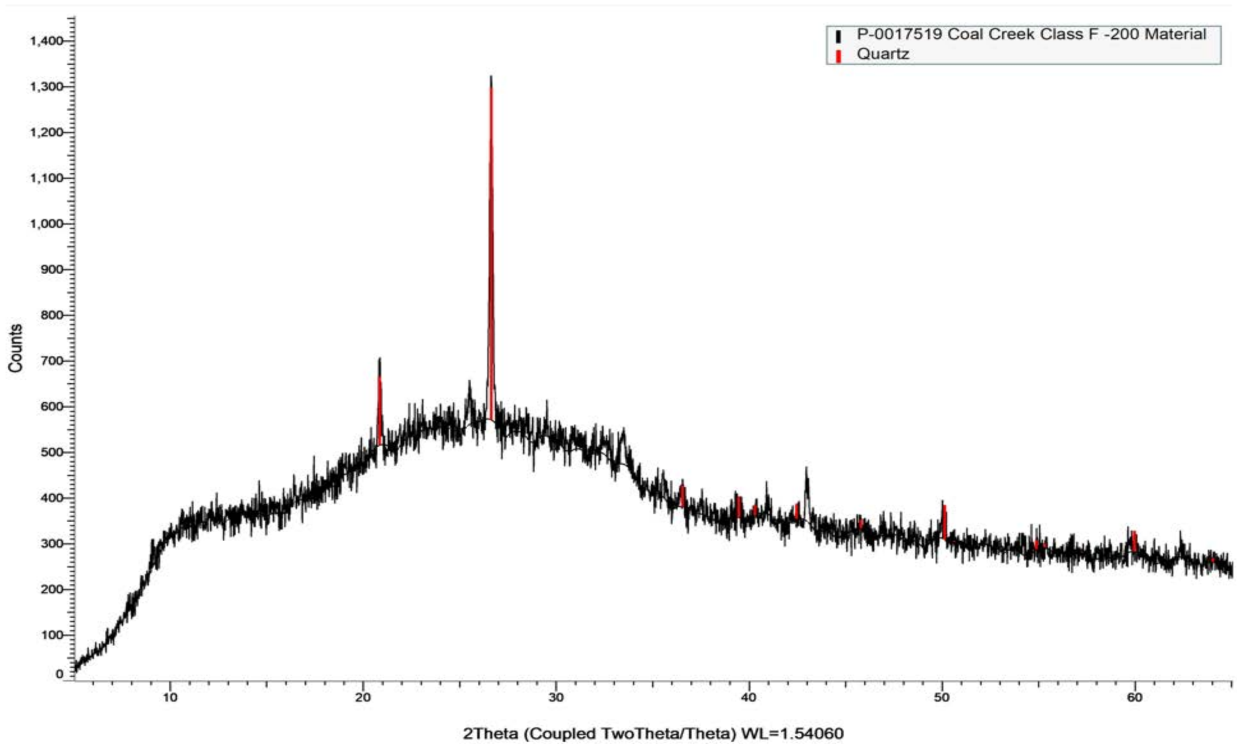
Weston



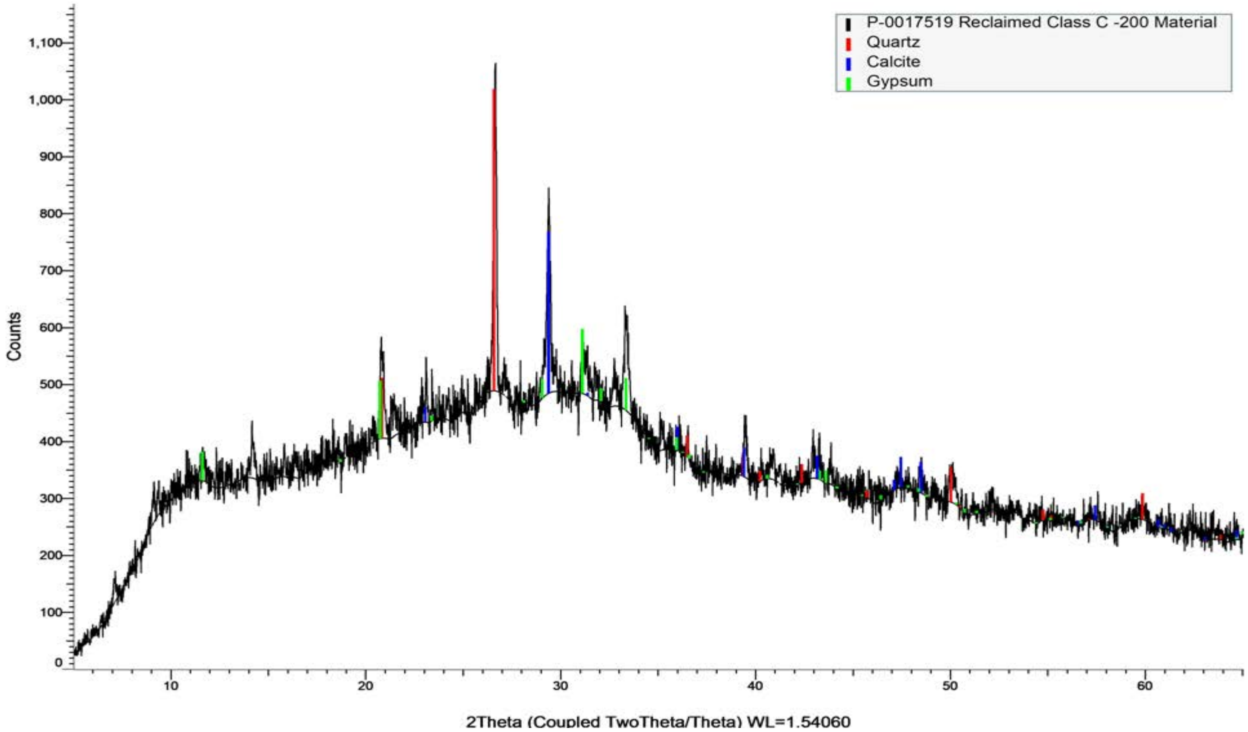
Reclaimed Ash



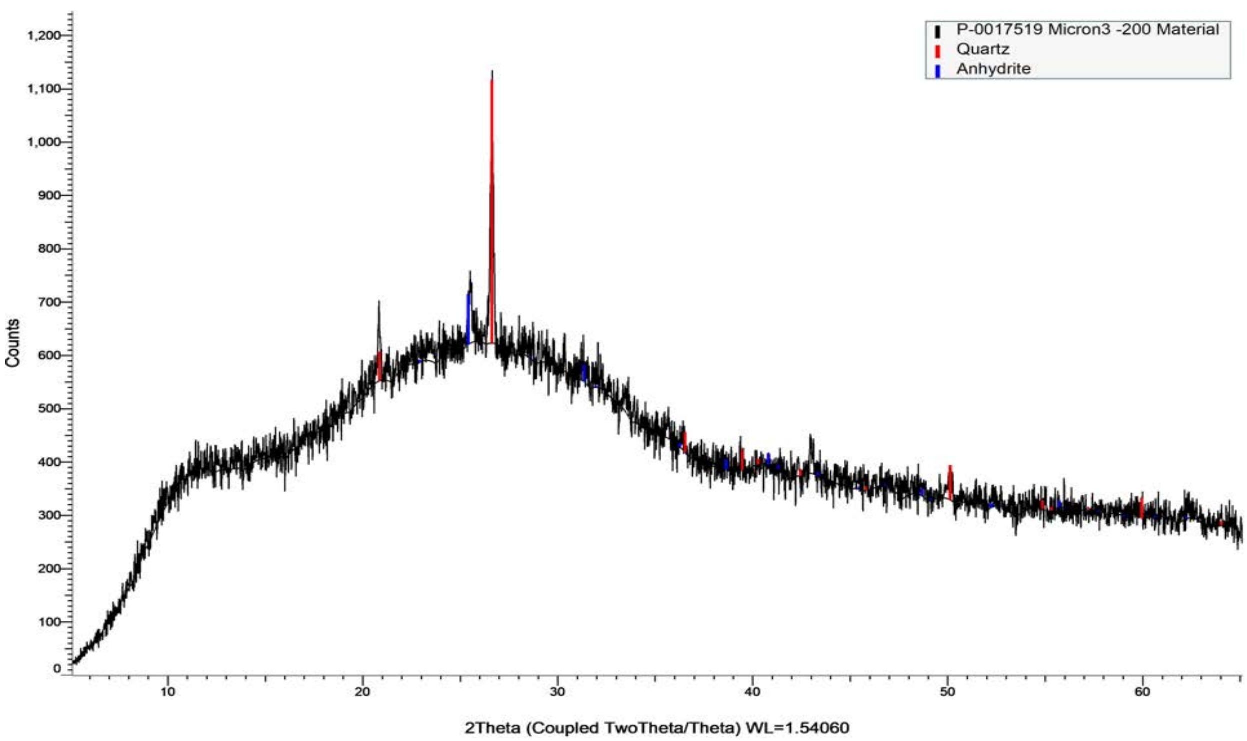
Coal Creek



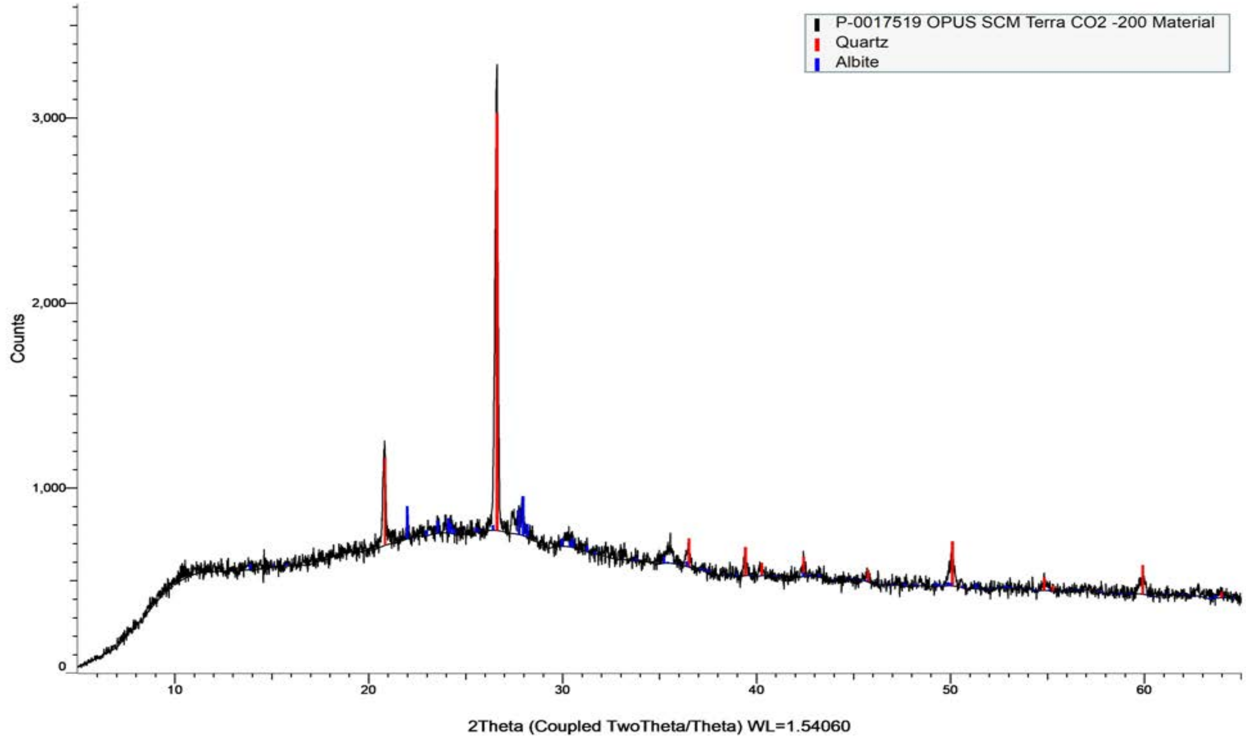
Marissa



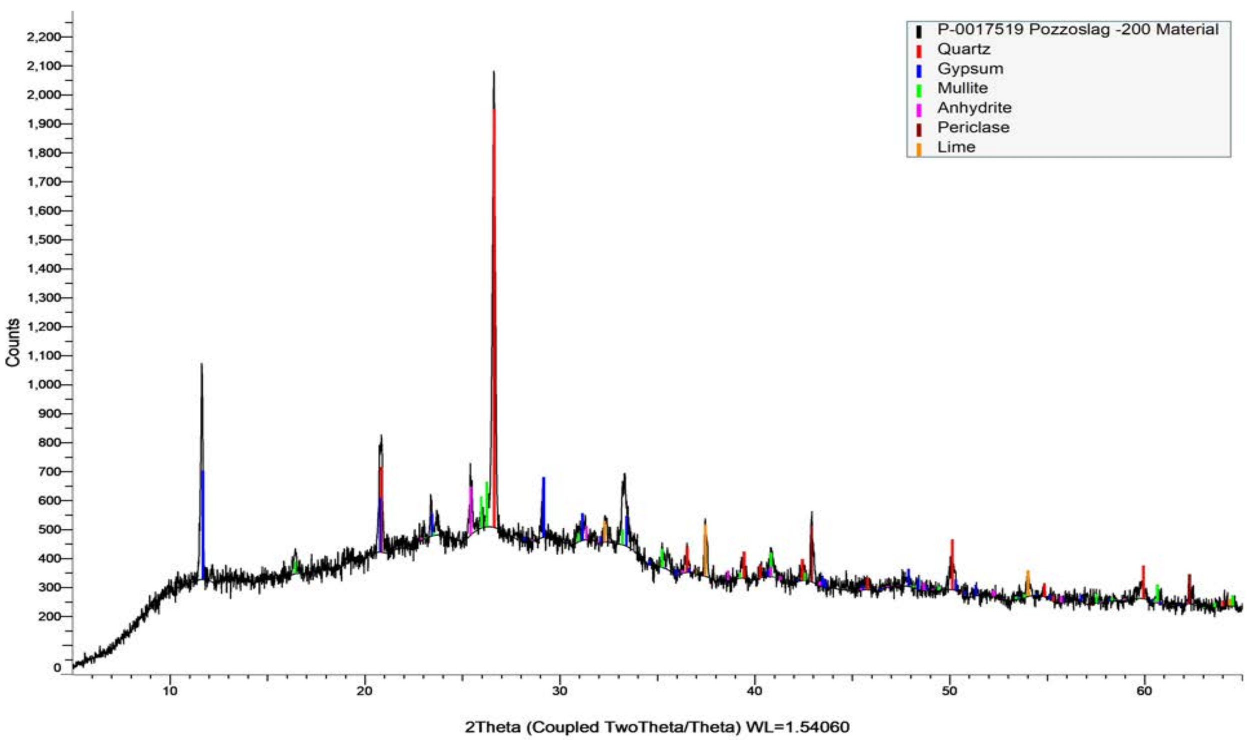
Micron^3



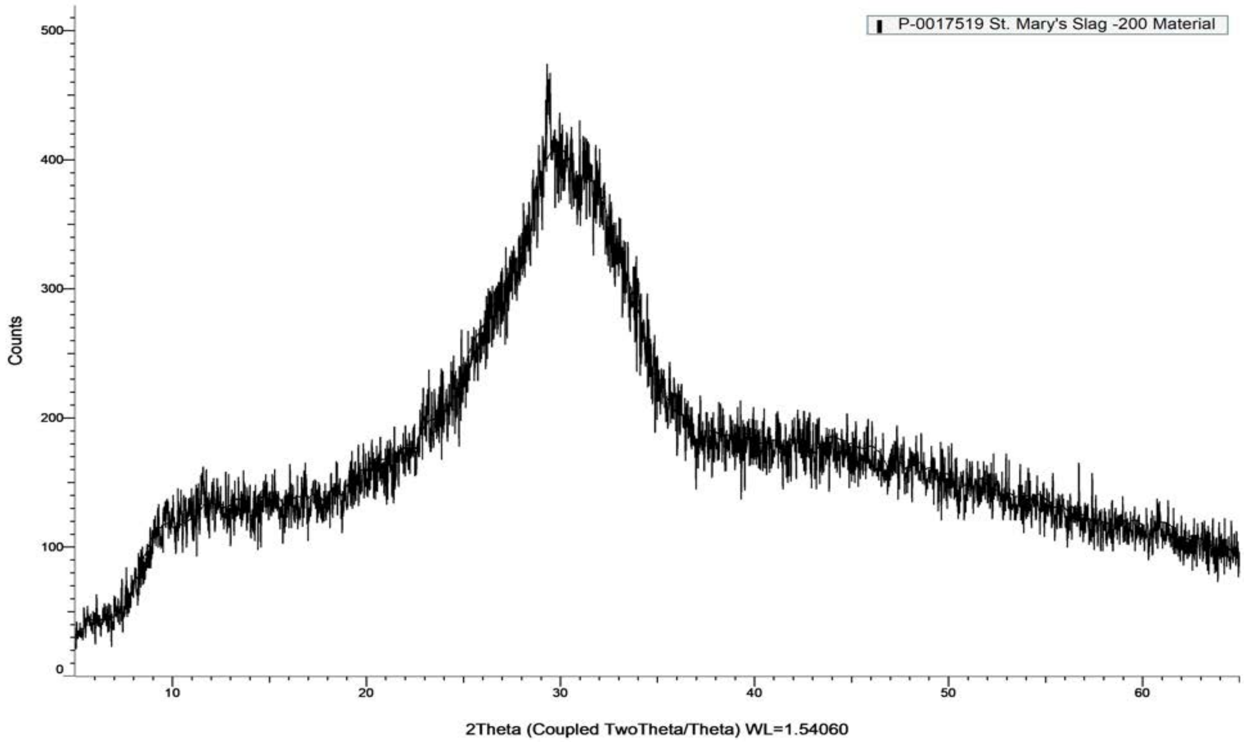
Opus



PozzoSlag



St Mary's Slag



ASTM C1897 – Reactivity

Table 4 and Table 5 show individual results of ASTM C1897.

Table 4 – Cummulative Heat Released at 7 days.

	Individual results		Average	Range	Range/average	Average of all replicates
Elm Road	299.4	326.5	313.0	27.1	8.7%	
	303.7	310.1	306.9	6.4	2.1%	309.9
Weston	351.0	333.5	342.3	17.5	5.1%	342.3
Reclaimed Ash	300.8	325.7	313.3	24.9	7.9%	
	323.8	326.2	325.0	2.4	0.7%	319.1
Coal Creek	212.6	222.2	217.4	9.6	4.4%	
	278.8	262.6	270.7	16.2	6.0%	244.1
Marissa	194.2	171.2	182.7	23.0	12.6%	
	222.8	198.0	210.4	24.8	11.8%	196.6
Micron3 + Marissa	260.7	253.3	257.0	7.4	2.9%	
	279.3	228.2	253.8	51.1	20.1%	
	290.0	283.0	286.5	7.0	2.4%	265.8
Opus	235.0	229.2	232.1	5.8	2.5%	
	254.3	264.8	259.6	10.5	4.0%	
	256.3	244.4	250.4	11.9	4.8%	247.3
PozzoSlag	307.6	312.6	310.1	5.0	1.6%	
	340.9	327.4	334.2	13.5	4.0%	
	337.3	324.4	330.9	12.9	3.9%	325.0
St Marys	450.2	440.1	445.2	10.1	2.3%	445.2

Average	5.68%
Max	20.14%
Min	0.74%

Table 5 – Bound water after 7 days.

	Individual results		Average	Range	Range/average	Average of all replicates
Elm Road	6.5101	6.6594	6.5848	0.1492	2.3%	
	6.5029	6.2426	6.3728	0.2603	4.1%	6.4788
Weston	6.7697	6.8685	6.8191	0.0988	1.4%	6.8191
Reclaimed	7.2488	7.5248	7.3868	0.2760	3.7%	
	6.2458	6.3278	6.2868	0.0820	1.3%	6.8368
Coal Creek	5.2851	5.9623	5.6237	0.6772	12.0%	
	5.8380	5.5450	5.6915	0.2930	5.1%	5.6576
Marissa	5.3416	4.6146	4.9781	0.7270	14.6%	
	5.0726	5.1885	5.1305	0.1159	2.3%	5.0543
Micron3 + Marissa	5.5422	6.0864	5.8143	0.5442	9.4%	
	6.8504	6.8511	6.8507	0.0007	0.0%	
	5.9277	6.1712	6.0495	0.2435	4.0%	6.2382
Opus	5.6513	5.5079	5.5796	0.1435	2.6%	
	5.6015	5.3166	5.4591	0.2848	5.2%	
	5.2707	5.3729	5.3218	0.1022	1.9%	5.4535
PozzoSlag	7.0958	6.9860	7.0409	0.1098	1.6%	
	6.7317	6.4448	6.5883	0.2869	4.4%	
	6.9218	6.9951	6.9584	0.0733	1.1%	6.8625
St Marys	7.2279	7.4612	7.3445	0.2334	3.2%	7.3445

Average	4.22%
Max	14.60%
Min	0.01%

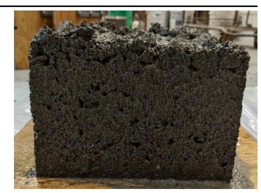
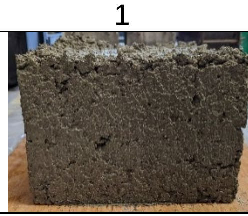
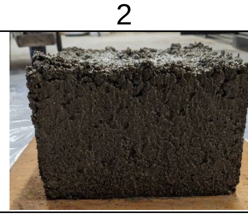
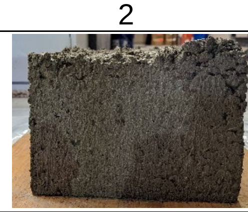
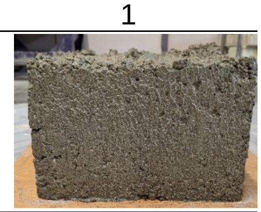
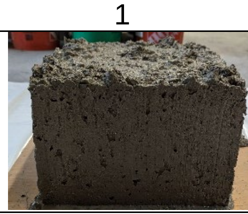
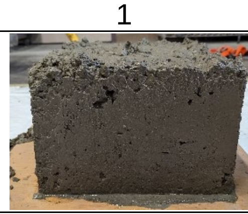
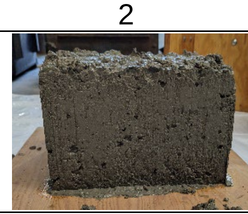
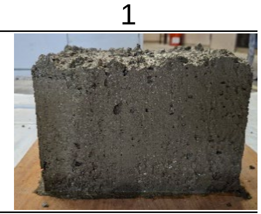
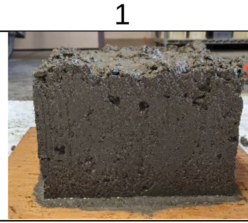
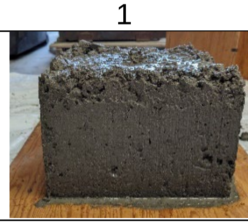
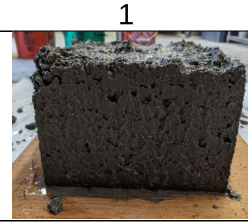
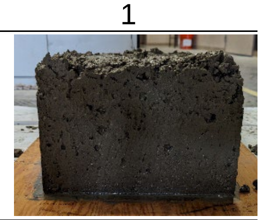
Concrete Fresh Properties

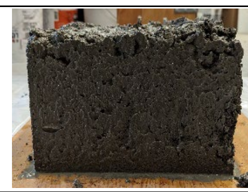
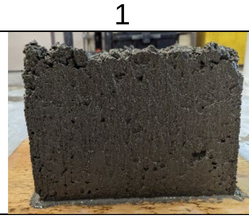
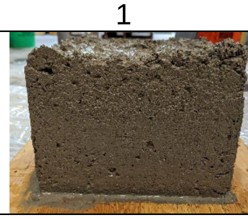
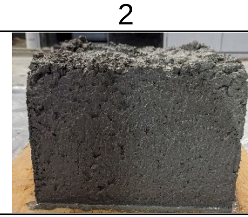
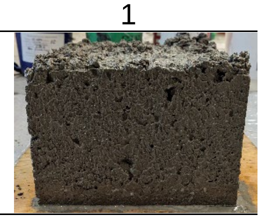
	Mixture	Control	Coal Creek	Elm Road	Weston	Reclaimed Ash	Marissa	Opus	PozzoSlag	Slag	Micron+Marissa	Liquid ASCM
	Date	10/25/2023	10/19/2023	10/19/2023	10/24/2023	11/7/2023	10/19/2023	10/23/2023	10/23/2023	10/23/2023	10/24/2023	10/25/2023
	LAB_ID	AET	AET	AET	AET	AET	AET	AET	AET	AET	AET	AET
Slump_In	Batch 1	1.5	1.75	1.00	1.5	1.5	1.50	1.00	2.00	0.75	1.5	2.0
	Batch 2	1.5	1.75	1.50	1.5	1.25	1.75	1.25	1.50	1.00	1.5	1.8
Air_Content_%	Batch 1	6.0	5.8	6.5	6.4	6.6	5.7	5.8	6.5	5.5	6.2	7.5
	Batch 2	6.0	6.0	6.0	6.3	6.6	6.0	6.2	6.0	5.4	6.2	6.5
SAM NO.	Batch 1	0.3	0.36	0.15	0.31	0.18	0.37	0.46	0.27	-	0.36	
	Batch 2	-	-	-	-	-	-	-	-	0.47	-	0.22
Unit_Weight_lb/ft3	Batch 1	147.7	148.5	146.9	151.7	145.7	148.5	147.7	147.0	150.0	150.9	147.3
	Batch 2	147.7	148.2	147.5	148.2	146.5	148.2	147.5	148.2	150.1	148	-
Temperature_°F	Batch 1	59	65	66	70	67	67	66	66	67	70	69
	Batch 2	69	66	66	70	67	67	66	67	67	70	-
Box_Rating_Side_1	Batch 1	2	1	3	1	1	1	1	1	2	1	1
Box_Rating_Side_2		2	1	3	2	1	2	1	1	2	1	2
Box_Rating_Side_3		1	1	3	2	2	1	1	1	1	2	1
Box_Rating_Side_4		1	1	2	1	1	2	2	2	2	1	1

Concrete Box Test

Table 4 presents pictures as well as the rating of all four sides of the box test of each of the tested mixtures.

Table 6 – AASHTO TP 137 – Box Test Pictures and Ratings.

Control				
	2	2	1	1
Elm Road				
	3	3	3	2
Weston				
	1	2	2	1
Reclaimed Ash				
	1	1	2	1
Coal Creek				
	1	1	1	1
Marissa				
	1	2	1	2

Opus	 1	 1	 1	 2
PozzoSlag	 2	 1	 1	 1
Slag	 2	 1	 2	 2
Micron3 + Marissa	 1	 1	 2	 1
LFA	 1	 2	 1	 1

Compressive Strength

Table 5 presents a summary of the compressive strength obtained at different ages.

Table 7 – Summary of Compressive Strength.

Age		Strength, psi										
		Control	Elm Road	Weston	Reclaimed Ash	Coal Creek	Marissa	Opus	PozzoSlag	Slag	Micron3+Marissa	Liquid ASCM
3 days	Specimen 1	5200	3590	3460	3250	3280	3500	3030	2600	4420	3310	5310
	Specimen 2	5480	3780	3410	3250	3350	3530	2990	2520	4450	3660	5440
	Average	5340	3680	3440	3250	3310	3510	3010	2560	4430	3490	5370
7 days	Specimen 1	5490	5390	5430	4460	4660	4470	4260	3720	5620	4410	6180
	Specimen 2	5980	5340	5270	4470	4640	4600	4040	3430	5970	4550	5890
	Average	5740	5360	5350	4470	4650	4530	4150	3570	5800	4480	6030
28 days	Specimen 1	6510	6610	7360	6080	5720	5700	6080	5010	7170	6310	7500
	Specimen 2	6760	6290	6650	6040	5980	6190	6130	4750	7950	6050	7250
	Average	6630	6450	7010	6060	5850	5940	6100	4880	7560	6180	7370
90 days	Specimen 1	7830	8240	8980	7270	5620	7780	7780	6490	9050	8970	7820
	Specimen 2	8220	7830	9240	7680	7530	8210	7820	6630	9760	8880	7660
	Average	8020	8030	9110	7470	6580	7990	7800	6560	9400	8930	7740

Flexural Strength

Table 6 presents a summary of the flexural strength obtained at different ages.

Table 8 – Summary of Flexural Strength.

		Strength, psi										
		Control	Elm Road	Weston	Reclaimed Ash	Coal Creek	Marissa	Opus	PozzoSlag	Slag	Micron3+Marissa	Liquid ASCM
3 days	Specimen 1	675	565	595	585	545	570	520	570	560	540	550
	Specimen 2	570	570	610	565	560	565	545	490	565	500	555
	Specimen 3	650	565	530	590	525	585	530	530	580	515	545
	Average	635	570	580	580	545	575	530	530	570	515	550
	Standard deviation	54.8	2.9	42.5	13.2	17.6	10.4	12.6	40.0	10.4	20.2	5.0
	COV, %	9%	1%	7%	2%	3%	2%	2%	8%	2%	4%	1%
7 days	Specimen 1	820	700	705	680	600	590	620	610	745	615	700
	Specimen 2	845	685	715	675	630	655	600	580	730	600	685
	Specimen 3	760	720	670	720	555	550	640	630	720	630	670
	Average	805	700	695	690	595	600	620	605	730	615	685
	Standard deviation	43.7	17.6	23.6	24.7	37.7	53.0	20.0	25.2	12.6	15.0	15.0
	COV, %	5%	3%	3%	4%	6%	9%	3%	4%	2%	2%	2%
28 days	Specimen 1	825	850	835	700	790	715	840	645	935	845	730
	Specimen 2	815	850	770	830	810	765	875	690	860	725	805
	Specimen 3	800	865	810	805	785	710	755	590	900	835	730
	Average	815	855	805	805	795	730	825	645	900	805	755
	Standard deviation	12.6	8.7	32.8	69.0	13.2	30.4	61.7	50.1	37.5	66.6	43.3
	COV, %	2%	1%	4%	9%	2%	4%	7%	8%	4%	8%	6%

Electrical Resistivity

Table 7 shows the results of the surface resistivity results.

Table 9 –Surface Resistivity According to AASHTO T 358.

		Surface resistivity corrected for curing conditions, kΩ.cm										
		Control	Elm Road	Weston	Reclaimed Ash	Coal Creek	Marissa	Opus	PozzoSlag	Slag	Micron3+ Marissa	Liquid ASCM
3 days	Specimen 1	3.8	3.0	3.5	2.8	3.3	3.0	3.4	3.4	4.0	3.1	4.4
	Specimen 2	3.7	3.0	3.2	2.7	3.3	3.0	3.5	3.4	3.8	3.1	4.5
	Specimen 3	3.8	3.0	3.4	3.0	4.3	3.1	3.3	3.5	3.8	3.0	4.2
	Average	3.8	3.0	3.4	2.8	3.6	3.0	3.4	3.4	3.9	3.1	4.4
	Standard deviation	0.1	0.0	0.2	0.1	0.6	0.1	0.1	0.1	0.1	0.0	0.1
	COV	2%	0%	5%	4%	17%	3%	4%	3%	3%	1%	3%
	Penetrability	High	High	High	High	High	High	High	High	High	High	High
7 days	Specimen 1	4.2	3.8	4.5	3.5	3.9	3.5	3.8	4.2	5.8	3.4	4.6
	Specimen 2	4.2	3.7	4.2	3.4	3.9	3.5	3.8	4.2	5.4	3.6	4.6
	Specimen 3	4.5	3.6	4.2	3.6	4.1	3.5	3.5	4.3	5.8	3.4	4.3
	Average	4.3	3.7	4.3	3.5	4.0	3.5	3.7	4.2	5.6	3.5	4.5
	Standard deviation	0.2	0.1	0.2	0.1	0.1	0.0	0.2	0.1	0.2	0.1	0.1
	COV	4%	2%	4%	3%	2%	0%	4%	2%	3%	3%	3%
	Penetrability	High	High	High	High	High	High	High	High	High	High	High

Surface resistivity corrected for curing conditions, kΩ.cm

		Control	Elm Road	Weston	Reclaimed Ash	Coal Creek	Marissa	Opus	PozzoSlag	Slag	Micron3+ Marissa	Control
28 days	Specimen 1	5.8	7.7	9.1	7.0	7.4	6.2	8.6	9.0	12.4	7.3	5.9
	Specimen 2	5.8	7.0	9.1	7.0	7.7	6.1	8.7	9.0	12.8	7.8	6.0
	Specimen 3	5.7	7.0	9.1	7.1	7.6	6.1	8.3	9.2	13.1	7.7	5.8
	Average	5.8	7.2	9.1	7.0	7.6	6.1	8.6	9.1	12.8	7.6	5.9
	Standard deviation	0.1	0.4	0.0	0.1	0.1	0.1	0.2	0.1	0.4	0.3	0.1
	COV	2%	5%	0%	1%	2%	2%	2%	1%	3%	3%	1%
	Penetrability	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Low	Moderate	Moderate
90 days	Specimen 1	6.9	14.8	17.1	11.7	16.1	15.8	23.8	17.1	16.7	19.9	10.6
	Specimen 2	7.6	14.7	16.9	12.0	16.5	15.9	23.9	16.7	16.9	20.5	10.0
	Specimen 3	8.3	15.0	16.7	11.9	16.2	16.2	24.3	17.0	17.4	20.9	10.4
	Average	7.6	14.8	16.9	11.9	16.3	16.0	24.0	16.9	17.0	20.4	10.3
	Standard deviation	0.7	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.4	0.5	0.3
	COV	9%	1%	1%	1%	1%	1%	1%	1%	2%	2%	3%
	Penetrability	Moderate	Low	Low	Low	Low	Low	Very Low	Low	Low	Low	Moderate
180 days	Specimen 1	9.0	21.7	23.3	15.9	23.9	27.4	41.5	26.0	19.6	38.4	11.4
	Specimen 2	8.7	21.0	24.0	15.7	25.9	27.3	41.0	25.7	20.1	39.0	11.6
	Specimen 3	9.2	20.9	24.1	16.1	25.7	28.6	41.9	24.8	19.9	38.5	12.3
	Average	9.0	21.2	23.8	15.9	25.2	27.8	41.5	25.5	19.9	38.7	11.8
	Standard deviation	0.2	0.4	0.5	0.2	1.1	0.7	0.4	0.6	0.3	0.3	0.5
	COV	3%	2%	2%	2%	4%	3%	1%	2%	1%	1%	4%
	Penetrability	Moderate	Very Low	Very Low	Low	Very Low	Very Low	Very Low	Very Low	Very Low	Very Low	Moderate

Freeze-Thaw Resistance

The summary of the freezing and thawing testing is shown in Table 7 and Table 8.

Table 10 – Summary of Relative Dynamic Modulus during Freezing and Thawing Cycles.

RDM at 300 Cycles	Control	Elm Road	Reclaimed Ash	Coal Creek	Marissa	Opus	PozzoSlag	Slag	Micron3+Marissa	Liquid ASCM
Specimen 1, %	100.0	97.2	97.2	97.1	98.1	98.1	98.2	99.1	99.1	97.1
Specimen 2, %	99.0	97.2	97.2	98.1	98.1	98.1	98.2	99.1	99.1	98.1
Specimen 3, %	97.1	97.2	97.2	98.1	98.1	99.0	98.1	100.0	97.2	98.1
Average, %	98.7	97.2	97.2	97.8	98.1	98.4	98.2	99.4	98.4	97.8
Standard deviation, %	1.5	0.0	0.0	0.5	0.0	0.6	0.0	0.5	1.1	0.6

Table 11 – Summary of Mass Change during Freezing and Thawing Cycles.

Mass Loss at 300 Cycles	Control	Elm Road	Reclaimed Ash	Coal Creek	Marissa	Opus	PozzoSlag	Slag	Micron3+Marissa	Liquid ASCM
Specimen 1, %	-0.6	-0.4	-0.7	-0.9	-0.3	-0.6	-0.6	-0.2	-0.7	-0.8
Specimen 2, %	-0.8	-0.3	-1.1	-0.9	-0.4	-0.9	-0.9	-0.2	-0.7	-0.8
Specimen 3, %	-0.7	-0.3	-0.9	-0.6	-0.2	-0.6	-0.7	-0.2	-0.4	-0.7
Average, %	-0.7	-0.3	-0.9	-0.8	-0.3	-0.7	-0.7	-0.2	-0.6	-0.8
Standard deviation, %	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.0	0.2	0.0

Shrinkage

The summary of length change due to drying (shrinkage) is shown in Table 7.

Table 12 – Summary of Length change.

Length change after 28 days drying	Control	Elm Road	Weston	Reclaimed Ash	Coal Creek	Marissa	Opus	PozzoSlag	Slag	Micron3+ Marissa	Liquid ASCM
Specimen 1, %	-0.026	-0.043	-0.038	-0.050	-0.047	-0.050	-0.039	-0.043	-0.049	-0.047	-0.029
Specimen 2, %	-0.026	-0.044	-0.038	-0.047	-0.047	-0.041	-0.041	-0.041	-0.04	-0.039	-0.031
Specimen 3, %	-0.025	-0.047	-0.037	-0.054	-0.046	-0.044	-0.04	-0.037	-0.04	-0.039	-0.03
Average, %	-0.026	-0.045	-0.038	-0.050	-0.047	-0.045	-0.040	-0.040	-0.043	-0.042	-0.030
Standard deviation, %	0.001	0.002	0.001	0.004	0.001	0.005	0.001	0.003	0.005	0.005	0.001

APPENDIX F

Flexural Strength

3 days

ANOVA: Single Factor

DESCRIPTION					Alpha	0.05		
Group	*Count*	*Sum*	*Mean*	*Variance*	*SS*	*Std Err*	*Lower*	*Upper*
Marissa	3	1720	573.33	108.33	216.67	15.29	541.62	605.05
Elm Road	3	1700	566.67	8.33	16.67	15.29	534.95	598.38
OPUS	3	1595	531.67	158.33	316.67	15.29	499.95	563.38
Micron+Ma	3	1555	518.33	408.33	816.67	15.29	486.62	550.05
Coal Creek	3	1630	543.33	308.33	616.67	15.29	511.62	575.05
PozzoSlag	3	1590	530.00	1600.00	3200.00	15.29	498.29	561.71
Slag	3	1705	568.33	108.33	216.67	15.29	536.62	600.05
Weston	3	1735	578.33	1808.33	3616.67	15.29	546.62	610.05
Control	3	1895	631.67	3008.33	6016.67	15.29	599.95	663.38
Reclaimed	3	1740	580.00	175.00	350.00	15.29	548.29	611.71
LASCM	3	1650	550.00	25.00	50.00	15.29	518.29	581.71

ANOVA								
Sources	*SS*	*df*	*MS*	*F*	*P value*	*Eta-sq*	*RMSSE*	*Omega Sq*
Between G	29904.55	10	2990.45	4.26	0.0022	0.6596	1.1920	0.4972
Within Gro	15433.33	22	701.52					
Total	45337.88	32	1416.81					

TUKEY HSD/KRAMER			alpha	0.05	
group	*mean*	*n*	*ss*	*df*	*q-crit*
Marissa	573.33	3	216.67		
Elm Road	566.67	3	16.67		
OPUS	531.67	3	316.67		
Micron+Ma	518.33	3	816.67		
Coal Creek	543.33	3	616.67		
PozzoSlag	530.00	3	3200.00		
Slag	568.33	3	216.67		
Weston	578.33	3	3616.67		
Control	631.67	3	6016.67		
Reclaimed	580.00	3	350.00		
LASCM	550.00	3	50.00		
		33	15433.33	22	5.056

group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*		*Statistical Significance*
Marissa	Elm Road	6.67	15.29	0.4360	-70.65	83.98	1.0000	77.32	0.2517		not significan
Marissa	OPUS	41.67	15.29	2.7248	-35.65	118.98	0.6954	77.32	1.5732		not significan
Marissa	Micron+Marissa	55.00	15.29	3.5967	-22.32	132.32	0.3333	77.32	2.0766		not significan
Marissa	Coal Creek	30.00	15.29	1.9618	-47.32	107.32	0.9391	77.32	1.1327		not significan
Marissa	PozzoSlag	43.33	15.29	2.8338	-33.98	120.65	0.6486	77.32	1.6361		not significan
Marissa	Slag	5.00	15.29	0.3270	-72.32	82.32	1.0000	77.32	0.1888		not significan
Marissa	Weston	5.00	15.29	0.3270	-72.32	82.32	1.0000	77.32	0.1888		not significan
Marissa	Control	58.33	15.29	3.8147	-18.98	135.65	0.2621	77.32	2.2024		not significan
Marissa	Reclaimed	6.67	15.29	0.4360	-70.65	83.98	1.0000	77.32	0.2517		not significan
Marissa	LASCM	23.33	15.29	1.5259	-53.98	100.65		77.32	0.8810		not significan

group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	*Statistical Significance*
Elm Road	OPUS	35.00	15.29	2.2888	-42.32	112.32	0.8583	77.32	1.3214	not significan
Elm Road	Micron+Marissa	48.33	15.29	3.1607	-28.98	125.65	0.5057	77.32	1.8249	not significan
Elm Road	Coal Creek	23.33	15.29	1.5259	-53.98	100.65	0.9885	77.32	0.8810	not significan
Elm Road	PozzoSlag	36.67	15.29	2.3978	-40.65	113.98	0.8226	77.32	1.3844	not significan
Elm Road	Slag	1.67	15.29	0.1090	-75.65	78.98	1.0000	77.32	0.0629	not significan
Elm Road	Weston	11.67	15.29	0.7629	-65.65	88.98	1.0000	77.32	0.4405	not significan
Elm Road	Control	65.00	15.29	4.2507	-12.32	142.32	0.1538	77.32	2.4541	not significan
Elm Road	Reclaimed	13.33	15.29	0.8719	-63.98	90.65	0.9999	77.32	0.5034	not significan
Elm Road	LASCM	16.67	15.29	1.0899	-60.65	93.98	0.9992	77.32	0.6293	not significan
OPUS	Micron+Marissa	13.33	15.29	0.8719	-63.98	90.65	0.9999	77.32	0.5034	not significan
OPUS	Coal Creek	11.67	15.29	0.7629	-65.65	88.98	1.0000	77.32	0.4405	not significan
OPUS	PozzoSlag	1.67	15.29	0.1090	-75.65	78.98	1.0000	77.32	0.0629	not significan
OPUS	Slag	36.67	15.29	2.3978	-40.65	113.98	0.8226	77.32	1.3844	not significan
OPUS	Weston	46.67	15.29	3.0517	-30.65	123.98	0.5530	77.32	1.7619	not significan
OPUS	Control	100.00	15.29	6.5395	22.68	177.32	0.0049	77.32	3.7756	significant
OPUS	Reclaimed	48.33	15.29	3.1607	-28.98	125.65	0.5057	77.32	1.8249	not significan
OPUS	LASCM	18.33	15.29	1.1989	-58.98	95.65	0.9982	77.32	0.6922	not significan
Micron+Marissa	Coal Creek	25.00	15.29	1.6349	-52.32	102.32	0.9813	77.32	0.9439	not significan
Micron+Marissa	PozzoSlag	11.67	15.29	0.7629	-65.65	88.98	1.0000	77.32	0.4405	not significan
Micron+Marissa	Slag	50.00	15.29	3.2697	-27.32	127.32	0.4596	77.32	1.8878	not significan
Micron+Marissa	Weston	60.00	15.29	3.9237	-17.32	137.32	0.2308	77.32	2.2653	not significan
Micron+Marissa	Control	113.33	15.29	7.4114	36.02	190.65	0.0012	77.32	4.2790	significant
Micron+Marissa	Reclaimed	61.67	15.29	4.0327	-15.65	138.98	0.2024	77.32	2.3283	not significan
Micron+Marissa	LASCM	31.67	15.29	2.0708	-45.65	108.98	0.9167	77.32	1.1956	not significan

group 1	group 2	mean	std err	q-stat	lower	upper	p-value	mean-crit	Cohen d	Statistical Significance
Coal Creek	PozzoSlag	13.33	15.29	0.8719	-63.98	90.65	0.9999	77.32	0.5034	not significan
Coal Creek	Slag	25.00	15.29	1.6349	-52.32	102.32	0.9813	77.32	0.9439	not significan
Coal Creek	Weston	35.00	15.29	2.2888	-42.32	112.32	0.8583	77.32	1.3214	not significan
Coal Creek	Control	88.33	15.29	5.7765	11.02	165.65	0.0166	77.32	3.3351	significant
Coal Creek	Reclaimed	36.67	15.29	2.3978	-40.65	113.98	0.8226	77.32	1.3844	not significan
Coal Creek	LASCM	6.67	15.29	0.4360	-70.65	83.98	1.0000	77.32	0.2517	not significan
PozzoSlag	Slag	38.33	15.29	2.5068	-38.98	115.65	0.7832	77.32	1.4473	not significan
PozzoSlag	Weston	48.33	15.29	3.1607	-28.98	125.65	0.5057	77.32	1.8249	not significan
PozzoSlag	Control	101.67	15.29	6.6485	24.35	178.98	0.0041	77.32	3.8385	significant
PozzoSlag	Reclaimed	50.00	15.29	3.2697	-27.32	127.32	0.4596	77.32	1.8878	not significan
PozzoSlag	LASCM	20.00	15.29	1.3079	-57.32	97.32	0.9964	77.32	0.7551	not significan
Slag	Weston	10.00	15.29	0.6539	-67.32	87.32	1.0000	77.32	0.3776	not significan
Slag	Control	63.33	15.29	4.1417	-13.98	140.65	0.1768	77.32	2.3912	not significan
Slag	Reclaimed	11.67	15.29	0.7629	-65.65	88.98	1.0000	77.32	0.4405	not significan
Slag	LASCM	18.33	15.29	1.1989	-58.98	95.65	0.9982	77.32	0.6922	not significan
Weston	Control	53.33	15.29	3.4877	-23.98	130.65	0.3730	77.32	2.0136	not significan
Weston	Reclaimed	1.67	15.29	0.1090	-75.65	78.98	1.0000	77.32	0.0629	not significan
Weston	LASCM	28.33	15.29	1.8528	-48.98	105.65	0.9571	77.32	1.0697	not significan
Control	Reclaimed	51.67	15.29	3.3787	-25.65	128.98	0.4152	77.32	1.9507	not significan
Control	LASCM	81.67	15.29	5.3406	4.35	158.98	0.0326	77.32	3.0834	significant
Reclaimed	LASCM	30.00	15.29	1.9618	-47.32	107.32	0.9391	77.32	1.1327	not significan

7 days

ANOVA: Single Factor

DESCRIPTION					Alpha	0.05		
Group	*Count*	*Sum*	*Mean*	*Variance*	*SS*	*Std Err*	*Lower*	*Upper*
Marissa	3	1795	598.33	2808.33	5616.67	16.75	563.60	633.07
Elm Road	3	2105	701.67	308.33	616.67	16.75	666.93	736.40
OPUS	3	1860	620.00	400.00	800.00	16.75	585.26	654.74
Micron+Marissa	3	1845	615.00	225.00	450.00	16.75	580.26	649.74
Coal Creek	3	1785	595.00	1425.00	2850.00	16.75	560.26	629.74
PozzoSlag	3	1820	606.67	633.33	1266.67	16.75	571.93	641.40
Slag	3	2195	731.67	158.33	316.67	16.75	696.93	766.40
Weston	3	2090	696.67	558.33	1116.67	16.75	661.93	731.40
Control	3	2425	808.33	1908.33	3816.67	16.75	773.60	843.07
Reclaimed	3	2075	691.67	608.33	1216.67	16.75	656.93	726.40
LASCM	3	2055	685.00	225.00	450.00	16.75	650.26	719.74

Sources	*SS*	*df*	*MS*	*F*	*P value*	*Eta-sq*	*RMSSE*	*Omega Sq*
Between Groups	136824.2	10	13682.42	16.26	5.94E-08	0.8808	2.3278	0.8222
Within Groups	18516.67	22	841.67					
Total	155340.9	32	4854.40					

TUKEY HSD/KRAMER			alpha	0.05	
group	*mean*	*n*	*ss*	*df*	*q-crit*
Marissa	598.33	3	5616.67		
Elm Road	701.67	3	616.67		
OPUS	620.00	3	800.00		
Micron+Marissa	615.00	3	450.00		
Coal Creek	595.00	3	2850.00		
PozzoSlag	606.67	3	1266.67		
Slag	731.67	3	316.67		
Weston	696.67	3	1116.67		
Control	808.33	3	3816.67		
Reclaimed	691.67	3	1216.67		
LASCM	685.00	3	450.00		
		33	18516.67	22	5.056

Q TEST										
group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	*Statistical Significance*
Marissa	Elm Road	103.33	16.75	6.1692	18.65	188.02	0.0089	84.69	3.5618	significant
Marissa	OPUS	21.67	16.75	1.2935	-63.02	106.35	0.9967	84.69	0.7468	not significant
Marissa	Micron+Marissa	16.67	16.75	0.9950	-68.02	101.35	0.9996	84.69	0.5745	not significant
Marissa	Coal Creek	3.33	16.75	0.1990	-81.35	88.02	1.0000	84.69	0.1149	not significant
Marissa	PozzoSlag	8.33	16.75	0.4975	-76.35	93.02	1.0000	84.69	0.2872	not significant
Marissa	Slag	133.33	16.75	7.9603	48.65	218.02	0.0005	84.69	4.5959	significant
Marissa	Weston	98.33	16.75	5.8707	13.65	183.02	0.0143	84.69	3.3895	significant
Marissa	Control	210.00	16.75	12.5375	125.31	294.69	0.0000	84.69	7.2385	significant
Marissa	Reclaimed	93.33	16.75	5.5722	8.65	178.02	0.0228	84.69	3.2171	significant
Marissa	LASCM	86.67	16.75	5.1742	1.98	171.35	0.0419	84.69	2.9873	significant

group 1	group 2	mean	std err	q-stat	lower	upper	p-value	mean-crit	Cohen d	Statistical Significance
Elm Road	OPUS	81.67	16.75	4.8757	-3.02	166.35	0.0651	84.69	2.8150	not significant
Elm Road	Micron+Marissa	86.67	16.75	5.1742	1.98	171.35	0.0419	84.69	2.9873	significant
Elm Road	Coal Creek	106.67	16.75	6.3682	21.98	191.35	0.0064	84.69	3.6767	significant
Elm Road	PozzoSlag	95.00	16.75	5.6717	10.31	179.69	0.0195	84.69	3.2746	significant
Elm Road	Slag	30.00	16.75	1.7911	-54.69	114.69	0.9654	84.69	1.0341	not significant
Elm Road	Weston	5.00	16.75	0.2985	-79.69	89.69	1.0000	84.69	0.1723	not significant
Elm Road	Control	106.67	16.75	6.3682	21.98	191.35	0.0064	84.69	3.6767	significant
Elm Road	Reclaimed	10.00	16.75	0.5970	-74.69	94.69	1.0000	84.69	0.3447	not significant
Elm Road	LASCM	16.67	16.75	0.9950	-68.02	101.35	0.9996	84.69	0.5745	not significant
OPUS	Micron+Marissa	5.00	16.75	0.2985	-79.69	89.69	1.0000	84.69	0.1723	not significant
OPUS	Coal Creek	25.00	16.75	1.4926	-59.69	109.69	0.9902	84.69	0.8617	not significant
OPUS	PozzoSlag	13.33	16.75	0.7960	-71.35	98.02	1.0000	84.69	0.4596	not significant
OPUS	Slag	111.67	16.75	6.6667	26.98	196.35	0.0040	84.69	3.8490	significant
OPUS	Weston	76.67	16.75	4.5772	-8.02	161.35	0.0993	84.69	2.6426	not significant
OPUS	Control	188.33	16.75	11.2439	103.65	273.02	0.0000	84.69	6.4917	significant
OPUS	Reclaimed	71.67	16.75	4.2787	-13.02	156.35	0.1483	84.69	2.4703	not significant
OPUS	LASCM	65.00	16.75	3.8806	-19.69	149.69	0.2428	84.69	2.2405	not significant
Micron+Marissa	Coal Creek	20.00	16.75	1.1940	-64.69	104.69	0.9983	84.69	0.6894	not significant
Micron+Marissa	PozzoSlag	8.33	16.75	0.4975	-76.35	93.02	1.0000	84.69	0.2872	not significant
Micron+Marissa	Slag	116.67	16.75	6.9653	31.98	201.35	0.0024	84.69	4.0214	significant
Micron+Marissa	Weston	81.67	16.75	4.8757	-3.02	166.35	0.0651	84.69	2.8150	not significant
Micron+Marissa	Control	193.33	16.75	11.5424	108.65	278.02	0.0000	84.69	6.6640	significant
Micron+Marissa	Reclaimed	76.67	16.75	4.5772	-8.02	161.35	0.0993	84.69	2.6426	not significant
Micron+Marissa	LASCM	70.00	16.75	4.1792	-14.69	154.69	0.1686	84.69	2.4128	not significant

group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	*Statistical Significance*
Coal Creek	PozzoSlag	11.67	16.75	0.6965	-73.02	96.35	1.0000	84.69	0.4021	not significant
Coal Creek	Slag	136.67	16.75	8.1593	51.98	221.35	0.0004	84.69	4.7108	significant
Coal Creek	Weston	101.67	16.75	6.0697	16.98	186.35	0.0104	84.69	3.5044	significant
Coal Creek	Control	213.33	16.75	12.7365	128.65	298.02	0.0000	84.69	7.3534	significant
Coal Creek	Reclaimed	96.67	16.75	5.7712	11.98	181.35	0.0167	84.69	3.3320	significant
Coal Creek	LASCM	90.00	16.75	5.3732	5.31	174.69	0.0310	84.69	3.1022	significant
PozzoSlag	Slag	125.00	16.75	7.4628	40.31	209.69	0.0011	84.69	4.3086	significant
PozzoSlag	Weston	90.00	16.75	5.3732	5.31	174.69	0.0310	84.69	3.1022	significant
PozzoSlag	Control	201.67	16.75	12.0400	116.98	286.35	0.0000	84.69	6.9513	significant
PozzoSlag	Reclaimed	85.00	16.75	5.0747	0.31	169.69	0.0486	84.69	2.9299	significant
PozzoSlag	LASCM	78.33	16.75	4.6767	-6.35	163.02	0.0864	84.69	2.7001	not significant
Slag	Weston	35.00	16.75	2.0896	-49.69	119.69	0.9124	84.69	1.2064	not significant
Slag	Control	76.67	16.75	4.5772	-8.02	161.35	0.0993	84.69	2.6426	not significant
Slag	Reclaimed	40.00	16.75	2.3881	-44.69	124.69	0.8260	84.69	1.3788	not significant
Slag	LASCM	46.67	16.75	2.7861	-38.02	131.35	0.6692	84.69	1.6086	not significant
Weston	Control	111.67	16.75	6.6667	26.98	196.35	0.0040	84.69	3.8490	significant
Weston	Reclaimed	5.00	16.75	0.2985	-79.69	89.69	1.0000	84.69	0.1723	not significant
Weston	LASCM	11.67	16.75	0.6965	-73.02	96.35	1.0000	84.69	0.4021	not significant
Control	Reclaimed	116.67	16.75	6.9653	31.98	201.35	0.0024	84.69	4.0214	significant
Control	LASCM	123.33	16.75	7.3633	38.65	208.02	0.0013	84.69	4.2512	significant
Reclaimed	LASCM	6.67	16.75	0.3980	-78.02	91.35	1.0000	84.69	0.2298	not significant

28 days

ANOVA: Single Factor

DESCRIPTION					Alpha	0.05		
Group	*Count*	*Sum*	*Mean*	*Variance*	*SS*	*Std Err*	*Lower*	*Upper*
Marissa	3	2190	730.00	925.00	1850.00	25.35	677.44	782.56
Elm Road	3	2565	855.00	75.00	150.00	25.35	802.44	907.56
OPUS	3	2470	823.33	3808.33	7616.67	25.35	770.77	875.90
Micron+Marissa	3	2405	801.67	4433.33	8866.67	25.35	749.10	854.23
Coal Creek	3	2385	795.00	175.00	350.00	25.35	742.44	847.56
PozzoSlag	3	1925	641.67	2508.33	5016.67	25.35	589.10	694.23
Slag	3	2695	898.33	1408.33	2816.67	25.35	845.77	950.90
Weston	3	2415	805.00	1075.00	2150.00	25.35	752.44	857.56
Control	3	2440	813.33	158.33	316.67	25.35	760.77	865.90
Reclaimed	3	2335	778.33	4758.33	9516.67	25.35	725.77	830.90
LASCM	3	2265	755.00	1875.00	3750.00	25.35	702.44	807.56

Sources	*SS*	*df*	*MS*	*F*	*P value*	*Eta-sq*	*RMSSE*	*Omega Sq*
Between Groups	134887.88	10.00	13488.79	7.00	0.0001	0.7608	1.5274	0.6451
Within Groups	42400.00	22.00	1927.27					
Total	177287.88	32.00	5540.25					

TUKEY HSD/KRAMER			alpha	0.05	
group	*mean*	*n*	*ss*	*df*	*q-crit*
Marissa	730.00	3	1850.00		
Elm Road	855.00	3	150.00		
OPUS	823.33	3	7616.67		
Micron+Marissa	801.67	3	8866.67		
Coal Creek	795.00	3	350.00		
PozzoSlag	641.67	3	5016.67		
Slag	898.33	3	2816.67		
Weston	805.00	3	2150.00		
Control	813.33	3	316.67		
Reclaimed	778.33	3	9516.67		
LASCM	755.00	3	3750.00		
		33	42400	22	5.056

Q TEST											
group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*		*Statistical Significance*
Marissa	Elm Road	125.00	25.35	4.93	-3.15	253.15	0.0600	128.1498	2.8473		not significant
Marissa	OPUS	93.33	25.35	3.68	-34.82	221.48	0.3040	128.1498	2.1260		not significant
Marissa	Micron+Marissa	71.67	25.35	2.83	-56.48	199.82	0.6513	128.1498	1.6325		not significant
Marissa	Coal Creek	65.00	25.35	2.56	-63.15	193.15	0.7609	128.1498	1.4806		not significant
Marissa	PozzoSlag	88.33	25.35	3.49	-39.82	216.48	0.3740	128.1498	2.0121		not significant
Marissa	Slag	168.33	25.35	6.64	40.18	296.48	0.0041	128.1498	3.8344		significant
Marissa	Weston	75.00	25.35	2.96	-53.15	203.15	0.5937	128.1498	1.7084		not significant
Marissa	Control	83.33	25.35	3.29	-44.82	211.48	0.4521	128.1498	1.8982		not significant
Marissa	Reclaimed	48.33	25.35	1.91	-79.82	176.48	0.9487	128.1498	1.1010		not significant
Marissa	LASCM	25.00	25.35	0.99	-103.15	153.15	0.9997	128.1498	0.5695		not significant

group 1	group 2	mean	std err	q-stat	lower	upper	p-value	mean-crit	Cohen d	Statistical Significance
Elm Road	OPUS	31.67	25.35	1.25	-96.48	159.82	0.9975	128.1498	0.7213	not significant
Elm Road	Micron+Marissa	53.33	25.35	2.10	-74.82	181.48	0.9090	128.1498	1.2149	not significant
Elm Road	Coal Creek	60.00	25.35	2.37	-68.15	188.15	0.8330	128.1498	1.3667	not significant
Elm Road	PozzoSlag	213.33	25.35	8.42	85.18	341.48	0.0002	128.1498	4.8595	significant
Elm Road	Slag	43.33	25.35	1.71	-84.82	171.48	0.9746	128.1498	0.9871	not significant
Elm Road	Weston	50.00	25.35	1.97	-78.15	178.15	0.9371	128.1498	1.1389	not significant
Elm Road	Control	41.67	25.35	1.64	-86.48	169.82	0.9805	128.1498	0.9491	not significant
Elm Road	Reclaimed	76.67	25.35	3.02	-51.48	204.82	0.5648	128.1498	1.7464	not significant
Elm Road	LASCM	100.00	25.35	3.95	-28.15	228.15	0.2249	128.1498	2.2779	not significant
OPUS	Micron+Marissa	21.67	25.35	0.85	-106.48	149.82	0.9999	128.1498	0.4935	not significant
OPUS	Coal Creek	28.33	25.35	1.12	-99.82	156.48	0.9990	128.1498	0.6454	not significant
OPUS	PozzoSlag	181.67	25.35	7.17	53.52	309.82	0.0018	128.1498	4.1381	significant
OPUS	Slag	75.00	25.35	2.96	-53.15	203.15	0.5937	128.1498	1.7084	not significant
OPUS	Weston	18.33	25.35	0.72	-109.82	146.48	1.0000	128.1498	0.4176	not significant
OPUS	Control	10.00	25.35	0.39	-118.15	138.15	1.0000	128.1498	0.2278	not significant
OPUS	Reclaimed	45.00	25.35	1.78	-83.15	173.15	0.9673	128.1498	1.0250	not significant
OPUS	LASCM	68.33	25.35	2.70	-59.82	196.48	0.7075	128.1498	1.5565	not significant
Micron+Marissa	Coal Creek	6.67	25.35	0.26	-121.48	134.82	1.0000	128.1498	0.1519	not significant
Micron+Marissa	PozzoSlag	160.00	25.35	6.31	31.85	288.15	0.0071	128.1498	3.6446	significant
Micron+Marissa	Slag	96.67	25.35	3.81	-31.48	224.82	0.2624	128.1498	2.2019	not significant
Micron+Marissa	Weston	3.33	25.35	0.13	-124.82	131.48	1.0000	128.1498	0.0759	not significant
Micron+Marissa	Control	11.67	25.35	0.46	-116.48	139.82	1.0000	128.1498	0.2658	not significant
Micron+Marissa	Reclaimed	23.33	25.35	0.92	-104.82	151.48	0.9998	128.1498	0.5315	not significant

group 1	group 2	mean	std err	q-stat	lower	upper	p-value	mean-crit	Cohen d	Statistical Significance
Coal Creek	PozzoSlag	153.33	25.35	6.05	25.18	281.48	0.0108	128.1498	3.4927	significant
Coal Creek	Slag	103.33	25.35	4.08	-24.82	231.48	0.1917	128.1498	2.3538	not significant
Coal Creek	Weston	10.00	25.35	0.39	-118.15	138.15	1.0000	128.1498	0.2278	not significant
Coal Creek	Control	18.33	25.35	0.72	-109.82	146.48	1.0000	128.1498	0.4176	not significant
Coal Creek	Reclaimed	16.67	25.35	0.66	-111.48	144.82	1.0000	128.1498	0.3796	not significant
Coal Creek	LASCM	40.00	25.35	1.58	-88.15	168.15	0.9854	128.1498	0.9111	not significant
PozzoSlag	Slag	256.67	25.35	10.13	128.52	384.82	0.0000	128.1498	5.8465	significant
PozzoSlag	Weston	163.33	25.35	6.44	35.18	291.48	0.0057	128.1498	3.7205	significant
PozzoSlag	Control	171.67	25.35	6.77	43.52	299.82	0.0033	128.1498	3.9103	significant
PozzoSlag	Reclaimed	136.67	25.35	5.39	8.52	264.82	0.0301	128.1498	3.1131	significant
PozzoSlag	LASCM	113.33	25.35	4.47	-14.82	241.48	0.1148	128.1498	2.5816	not significant
Slag	Weston	93.33	25.35	3.68	-34.82	221.48	0.3040	128.1498	2.1260	not significant
Slag	Control	85.00	25.35	3.35	-43.15	213.15	0.4252	128.1498	1.9362	not significant
Slag	Reclaimed	120.00	25.35	4.73	-8.15	248.15	0.0797	128.1498	2.7334	not significant
Slag	LASCM	143.33	25.35	5.66	15.18	271.48	0.0201	128.1498	3.2649	significant
Weston	Control	8.33	25.35	0.33	-119.82	136.48	1.0000	128.1498	0.1898	not significant
Weston	Reclaimed	26.67	25.35	1.05	-101.48	154.82	0.9994	128.1498	0.6074	not significant
Weston	LASCM	50.00	25.35	1.97	-78.15	178.15	0.9371	128.1498	1.1389	not significant
Control	Reclaimed	35.00	25.35	1.38	-93.15	163.15	0.9946	128.1498	0.7973	not significant
Control	LASCM	58.33	25.35	2.30	-69.82	186.48	0.8544	128.1498	1.3288	not significant
Reclaimed	LASCM	23.33	25.35	0.92	-104.82	151.48	0.9998	128.1498	0.5315	not significant

Freeze-Thaw Resistance

Mass Change

ANOVA: Single Factor

DESCRIPTION					Alpha	0.05		
Group	*Count*	*Sum*	*Mean*	*Variance*	*SS*	*Std Err*	*Lower*	*Upper*
Marissa	3	-0.9151	-0.3050	0.0035	0.0070	0.0727	-0.4567	-0.1534
Elm Road	3	-1.0334	-0.3445	0.0028	0.0057	0.0727	-0.4961	-0.1928
OPUS	3	-2.1269	-0.7090	0.0171	0.0343	0.0727	-0.8606	-0.5573
Micron+Marissa	3	-1.7675	-0.5892	0.0304	0.0607	0.0727	-0.7408	-0.4375
Coal Creek	3	-2.2999	-0.7666	0.0310	0.0621	0.0727	-0.9183	-0.6150
PozzoSlag	3	-2.2039	-0.7346	0.0193	0.0386	0.0727	-0.8863	-0.5830
Slag	3	-0.5885	-0.1962	0.0009	0.0019	0.0727	-0.3478	-0.0445
Control	3	-2.1445	-0.7148	0.0132	0.0264	0.0727	-0.8665	-0.5632
Reclaimed	3	-2.6710	-0.8903	0.0377	0.0755	0.0727	-1.0420	-0.7387
LASCM	3	-2.3657	-0.7886	0.0025	0.0050	0.0727	-0.9402	-0.6369

Sources	*SS*	*df*	*MS*	*F*	*P value*	*Eta-sq*	*RMSSE*	*Omega Sq*
Between Groups	1.518429	9	0.1687	10.6412	7.13E-06	0.8272	1.8834	0.7431
Within Groups	0.317096	20	0.0159					
Total	1.835525	29	0.0633					

TUKEY HSD/KRAMER			alpha	0.05	
group	*mean*	*n*	*ss*	*df*	*q-crit*
Marissa	-0.3050	3	0.0070		
Elm Road	-0.3445	3	0.0057		
OPUS	-0.7090	3	0.0343		
Micron+Marissa	-0.5892	3	0.0607		
Coal Creek	-0.7666	3	0.0621		
PozzoSlag	-0.7346	3	0.0386		
Slag	-0.1962	3	0.0019		
Control	-0.7148	3	0.0264		
Reclaimed	-0.8903	3	0.0755		
LASCM	-0.7886	3	0.0050		
		30	0.3171	20	5.008

Q TEST										
group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	*Statistical Significance*
Marissa	Elm Road	0.0394	0.0727	0.5426	-0.3246	0.4035	1.0000	0.3641	0.3133	not significant
Marissa	OPUS	0.4039	0.0727	5.5565	0.0399	0.7680	0.0223	0.3641	3.2081	significant
Marissa	Micron+Marissa	0.2841	0.0727	3.9086	-0.0799	0.6482	0.2142	0.3641	2.2566	not significant
Marissa	Coal Creek	0.4616	0.0727	6.3495	0.0975	0.8257	0.0067	0.3641	3.6659	significant
Marissa	PozzoSlag	0.4296	0.0727	5.9095	0.0655	0.7937	0.0131	0.3641	3.4119	significant
Marissa	Slag	0.1089	0.0727	1.4973	-0.2552	0.4729	0.9836	0.3641	0.8645	not significant
Marissa	Control	0.4098	0.0727	5.6370	0.0457	0.7739	0.0198	0.3641	3.2545	significant
Marissa	Reclaimed	0.5853	0.0727	8.0514	0.2212	0.9494	0.0005	0.3641	4.6485	significant
Marissa	LASCM	0.4835	0.0727	6.6512	0.1195	0.8476	0.0042	0.3641	3.8401	significant

group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	*Statistical Significance*
Elm Road	OPUS	0.3645	0.0727	5.0139	0.0004	0.7286	0.0496	0.3641	2.8948	significant
Elm Road	Micron+Marissa	0.2447	0.0727	3.3659	-0.1194	0.6088	0.3856	0.3641	1.9433	not significant
Elm Road	Coal Creek	0.4221	0.0727	5.8069	0.0581	0.7862	0.0153	0.3641	3.3526	significant
Elm Road	PozzoSlag	0.3902	0.0727	5.3669	0.0261	0.7542	0.0296	0.3641	3.0986	significant
Elm Road	Slag	0.1483	0.0727	2.0400	-0.2158	0.5124	0.8989	0.3641	1.1778	not significant
Elm Road	Control	0.3703	0.0727	5.0943	0.0063	0.7344	0.0441	0.3641	2.9412	significant
Elm Road	Reclaimed	0.5459	0.0727	7.5087	0.1818	0.9099	0.0011	0.3641	4.3352	significant
Elm Road	LASCM	0.4441	0.0727	6.1086	0.0800	0.8081	0.0097	0.3641	3.5268	significant
OPUS	Micron+Marissa	0.1198	0.0727	1.6480	-0.2443	0.4839	0.9698	0.3641	0.9514	not significant
OPUS	Coal Creek	0.0576	0.0727	0.7930	-0.3064	0.4217	0.9999	0.3641	0.4578	not significant
OPUS	PozzoSlag	0.0257	0.0727	0.3530	-0.3384	0.3897	1.0000	0.3641	0.2038	not significant
OPUS	Slag	0.5128	0.0727	7.0538	0.1487	0.8769	0.0022	0.3641	4.0725	significant
OPUS	Control	0.0058	0.0727	0.0805	-0.3582	0.3699	1.0000	0.3641	0.0465	not significant
OPUS	Reclaimed	0.1814	0.0727	2.4949	-0.1827	0.5454	0.7484	0.3641	1.4404	not significant
OPUS	LASCM	0.0796	0.0727	1.0947	-0.2845	0.4437	0.9982	0.3641	0.6320	not significant
Micron+Marissa	Coal Creek	0.1775	0.0727	2.4410	-0.1866	0.5415	0.7694	0.3641	1.4093	not significant
Micron+Marissa	PozzoSlag	0.1455	0.0727	2.0010	-0.2186	0.5095	0.9085	0.3641	1.1553	not significant
Micron+Marissa	Slag	0.3930	0.0727	5.4059	0.0289	0.7571	0.0280	0.3641	3.1211	significant
Micron+Marissa	Control	0.1257	0.0727	1.7284	-0.2384	0.4897	0.9597	0.3641	0.9979	not significant
Micron+Marissa	Reclaimed	0.3012	0.0727	4.1428	-0.0629	0.6652	0.1611	0.3641	2.3919	not significant
Micron+Marissa	LASCM	0.1994	0.0727	2.7427	-0.1647	0.5635	0.6455	0.3641	1.5835	not significant

group 1	group 2	mean	std err	q-stat	lower	upper	p-value	mean-crit	Cohen d	Statistical Significance
Coal Creek	PozzoSlag	0.0320	0.0727	0.4400	-0.3321	0.3961	1.0000	0.3641	0.2540	not significant
Coal Creek	Slag	0.5704	0.0727	7.8468	0.2064	0.9345	0.0007	0.3641	4.5304	significant
Coal Creek	Control	0.0518	0.0727	0.7125	-0.3123	0.4159	0.9999	0.3641	0.4114	not significant
Coal Creek	Reclaimed	0.1237	0.0727	1.7019	-0.2403	0.4878	0.9633	0.3641	0.9826	not significant
Coal Creek	LASCM	0.0219	0.0727	0.3017	-0.3421	0.3860	1.0000	0.3641	0.1742	not significant
PozzoSlag	Slag	0.5385	0.0727	7.4069	0.1744	0.9025	0.0013	0.3641	4.2764	significant
PozzoSlag	Control	0.0198	0.0727	0.2726	-0.3443	0.3839	1.0000	0.3641	0.1574	not significant
PozzoSlag	Reclaimed	0.1557	0.0727	2.1418	-0.2084	0.5198	0.8712	0.3641	1.2366	not significant
PozzoSlag	LASCM	0.0539	0.0727	0.7417	-0.3102	0.4180	0.9999	0.3641	0.4282	not significant
Slag	Control	0.5186	0.0727	7.1343	0.1546	0.8827	0.0020	0.3641	4.1190	significant
Slag	Reclaimed	0.6942	0.0727	9.5487	0.3301	1.0582	0.0001	0.3641	5.5130	significant
Slag	LASCM	0.5924	0.0727	8.1485	0.2283	0.9564	0.0004	0.3641	4.7046	significant
Control	Reclaimed	0.1755	0.0727	2.4144	-0.1885	0.5396	0.7795	0.3641	1.3940	not significant
Control	LASCM	0.0737	0.0727	1.0142	-0.2903	0.4378	0.9990	0.3641	0.5856	not significant
Reclaimed	LASCM	0.1018	0.0727	1.4002	-0.2623	0.4659	0.9896	0.3641	0.8084	not significant

Surface Resistivity

3 days

ANOVA: Single Factor

DESCRIPTION					Alpha	0.05		
Group	*Count*	*Sum*	*Mean*	*Variance*	*SS*	*Std Err*	*Lower*	*Upper*
Control	3	11.2698	3.7566	0.0064	0.0128	0.1194	3.5089	4.0042
Elm Road	3	9.1117	3.0372	0.0000	0.0000	0.1194	2.7896	3.2849
Weston	3	10.1508	3.3836	0.0277	0.0554	0.1194	3.1359	3.6313
Reclaimed Ash	3	8.4723	2.8241	0.0149	0.0298	0.1194	2.5764	3.0718
Coal Creek	3	10.8701	3.6234	0.3599	0.7198	0.1194	3.3757	3.8710
Marissa	3	9.1117	3.0372	0.0064	0.0128	0.1194	2.7896	3.2849
Opus	3	10.1508	3.3836	0.0149	0.0298	0.1194	3.1359	3.6313
PozzoSlag	3	10.2307	3.4102	0.0085	0.0170	0.1194	3.1626	3.6579
Slag	3	11.5895	3.8632	0.0149	0.0298	0.1194	3.6155	4.1108
Micron3+Marissa	3	9.2716	3.0905	0.0021	0.0043	0.1194	2.8429	3.3382
Liquid ASCM	3	13.1081	4.3694	0.0149	0.0298	0.1194	4.1217	4.6170

ANOVA								
Sources	*SS*	*df*	*MS*	*F*	*P value*	*Eta-sq*	*RMSSE*	*Omega Sq*
Between Groups	6.028307	10	0.6028	14.0905	2.19E-07	0.8650	2.1672	0.7987
Within Groups	0.941221	22	0.0428					
Total	6.969528	32	0.2178					

TUKEY HSD/KRAMER			alpha	0.05	
group	*mean*	*n*	*ss*	*df*	*q-crit*
Control	3.7566	3	0.0128		
Elm Road	3.0372	3	0.0000		
Weston	3.3836	3	0.0554		
Reclaimed Ash	2.8241	3	0.0298		
Coal Creek	3.6234	3	0.7198		
Marissa	3.0372	3	0.0128		
Opus	3.3836	3	0.0298		
PozzoSlag	3.4102	3	0.0170		
Slag	3.8632	3	0.0298		
Micron3+Mariss	3.0905	3	0.0043		
Liquid ASCM	4.3694	3	0.0298		
		33	0.9412	22	5.056

group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	Statistical Significance
Control	Elm Road	0.7193	0.1194	6.0237	0.1156	1.3231	0.0112	0.6038	3.4778	significant
Control	Weston	0.3730	0.1194	3.1234	-0.2308	0.9768	0.5217	0.6038	1.8033	not significant
Control	Reclaimed Ash	0.9325	0.1194	7.8085	0.3287	1.5363	0.0006	0.6038	4.5082	significant
Control	Coal Creek	0.1332	0.1194	1.1155	-0.4706	0.7370	0.9990	0.6038	0.6440	not significant
Control	Marissa	0.7193	0.1194	6.0237	0.1156	1.3231	0.0112	0.6038	3.4778	significant
Control	Opus	0.3730	0.1194	3.1234	-0.2308	0.9768	0.5217	0.6038	1.8033	not significant
Control	PozzoSlag	0.3464	0.1194	2.9003	-0.2574	0.9501	0.6195	0.6038	1.6745	not significant
Control	Slag	0.1066	0.1194	0.8924	-0.4972	0.7104	0.9999	0.6038	0.5152	not significant
Control	Micron3+Mariss	0.6661	0.1194	5.5775	0.0623	1.2698	0.0226	0.6038	3.2202	significant
Control	Liquid ASCM	0.6128	0.1194	5.1313	0.0090	1.2166	0.0447	0.6038	2.9626	significant

group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	Statistical Significance
Elm Road	Weston	0.3464	0.1194	2.9003	-0.2574	0.9501	0.6195	0.6038	1.6745	not significant
Elm Road	Reclaimed Ash	0.2131	0.1194	1.7848	-0.3906	0.8169	0.9662	0.6038	1.0305	not significant
Elm Road	Coal Creek	0.5861	0.1194	4.9082	-0.0176	1.1899	0.0621	0.6038	2.8338	not significant
Elm Road	Marissa	0.0000	0.1194	0.0000	-0.6038	0.6038	0.0000	0.6038	0.0000	not significant
Elm Road	Opus	0.3464	0.1194	2.9003	-0.2574	0.9501	0.6195	0.6038	1.6745	not significant
Elm Road	PozzoSlag	0.3730	0.1194	3.1234	-0.2308	0.9768	0.5217	0.6038	1.8033	not significant
Elm Road	Slag	0.8259	0.1194	6.9161	0.2221	1.4297	0.0027	0.6038	3.9930	significant
Elm Road	Micron3+Mariss	0.0533	0.1194	0.4462	-0.5505	0.6571	1.0000	0.6038	0.2576	not significant
Elm Road	Liquid ASCM	1.3321	0.1194	11.1550	0.7283	1.9359	0.0000	0.6038	6.4404	significant
Weston	Reclaimed Ash	0.5595	0.1194	4.6851	-0.0443	1.1633	0.0854	0.6038	2.7049	not significant
Weston	Coal Creek	0.2398	0.1194	2.0079	-0.3640	0.8436	0.9302	0.6038	1.1593	not significant
Weston	Marissa	0.3464	0.1194	2.9003	-0.2574	0.9501	0.6195	0.6038	1.6745	not significant
Weston	Opus	0.0000	0.1194	0.0000	-0.6038	0.6038	1.0000	0.6038	0.0000	not significant
Weston	PozzoSlag	0.0266	0.1194	0.2231	-0.5771	0.6304	1.0000	0.6038	0.1288	not significant
Weston	Slag	0.4796	0.1194	4.0158	-0.1242	1.0833	0.2066	0.6038	2.3185	not significant
Weston	Micron3+Mariss	0.2931	0.1194	2.4541	-0.3107	0.8969	0.8027	0.6038	1.4169	not significant
Weston	Liquid ASCM	0.9858	0.1194	8.2547	0.3820	1.5896	0.0003	0.6038	4.7659	significant
Reclaimed Ash	Coal Creek	0.7993	0.1194	6.6930	0.1955	1.4031	0.0038	0.6038	3.8642	significant
Reclaimed Ash	Marissa	0.2131	0.1194	1.7848	-0.3906	0.8169	0.9662	0.6038	1.0305	not significant
Reclaimed Ash	Opus	0.5595	0.1194	4.6851	-0.0443	1.1633	0.0854	0.6038	2.7049	not significant
Reclaimed Ash	PozzoSlag	0.5861	0.1194	4.9082	-0.0176	1.1899	0.0621	0.6038	2.8338	not significant
Reclaimed Ash	Slag	1.0391	0.1194	8.7009	0.4353	1.6428	0.0001	0.6038	5.0235	significant
Reclaimed Ash	Micron3+Mariss	0.2664	0.1194	2.2310	-0.3374	0.8702	0.8755	0.6038	1.2881	not significant
Reclaimed Ash	Liquid ASCM	1.5453	0.1194	12.9398	0.9415	2.1490	0.0000	0.6038	7.4708	significant

group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	Statistical Significance
Coal Creek	Marissa	0.5861	0.1194	4.9082	-0.0176	1.1899	0.0621	0.6038	2.8338	not significant
Coal Creek	Opus	0.2398	0.1194	2.0079	-0.3640	0.8436	0.9302	0.6038	1.1593	not significant
Coal Creek	PozzoSlag	0.2131	0.1194	1.7848	-0.3906	0.8169	0.9662	0.6038	1.0305	not significant
Coal Creek	Slag	0.2398	0.1194	2.0079	-0.3640	0.8436	0.9302	0.6038	1.1593	not significant
Coal Creek	Micron3+Mariss	0.5328	0.1194	4.4620	-0.0709	1.1366	0.1162	0.6038	2.5761	not significant
Coal Creek	Liquid ASCM	0.7460	0.1194	6.2468	0.1422	1.3498	0.0078	0.6038	3.6066	significant
Marissa	Opus	0.3464	0.1194	2.9003	-0.2574	0.9501	0.6195	0.6038	1.6745	not significant
Marissa	PozzoSlag	0.3730	0.1194	3.1234	-0.2308	0.9768	0.5217	0.6038	1.8033	not significant
Marissa	Slag	0.8259	0.1194	6.9161	0.2221	1.4297	0.0027	0.6038	3.9930	significant
Marissa	Micron3+Mariss	0.0533	0.1194	0.4462	-0.5505	0.6571	1.0000	0.6038	0.2576	not significant
Marissa	Liquid ASCM	1.3321	0.1194	11.1550	0.7283	1.9359	0.0000	0.6038	6.4404	significant
Opus	PozzoSlag	0.0266	0.1194	0.2231	-0.5771	0.6304	1.0000	0.6038	0.1288	not significant
Opus	Slag	0.4796	0.1194	4.0158	-0.1242	1.0833	0.2066	0.6038	2.3185	not significant
Opus	Micron3+Mariss	0.2931	0.1194	2.4541	-0.3107	0.8969	0.8027	0.6038	1.4169	not significant
Opus	Liquid ASCM	0.9858	0.1194	8.2547	0.3820	1.5896	0.0003	0.6038	4.7659	significant
PozzoSlag	Slag	0.4529	0.1194	3.7927	-0.1509	1.0567	0.2688	0.6038	2.1897	not significant
PozzoSlag	Micron3+Mariss	0.3197	0.1194	2.6772	-0.2841	0.9235	0.7153	0.6038	1.5457	not significant
PozzoSlag	Liquid ASCM	0.9591	0.1194	8.0316	0.3553	1.5629	0.0004	0.6038	4.6371	significant
Slag	Micron3+Mariss	0.7726	0.1194	6.4699	0.1688	1.3764	0.0055	0.6038	3.7354	significant
Slag	Liquid ASCM	0.5062	0.1194	4.2389	-0.0976	1.1100	0.1561	0.6038	2.4473	not significant
Micron3+Marissa	Liquid ASCM	1.2788	0.1194	10.7088	0.6751	1.8826	0.0000	0.6038	6.1827	significant

7 days

ANOVA: Single Factor

DESCRIPTION					Alpha	0.05		
Group	*Count*	*Sum*	*Mean*	*Variance*	*SS*	*Std Err*	*Lower*	*Upper*
Control	3	12.8683	4.2894	0.0277	0.0554	0.0745	4.1349	4.4439
Elm Road	3	11.0300	3.6767	0.0064	0.0128	0.0745	3.5222	3.8312
Weston	3	12.8683	4.2894	0.0277	0.0554	0.0745	4.1349	4.4439
Reclaimed Ash	3	10.4705	3.4902	0.0149	0.0298	0.0745	3.3357	3.6447
Coal Creek	3	11.9092	3.9697	0.0085	0.0170	0.0745	3.8152	4.1242
Marissa	3	10.5504	3.5168	0.0000	0.0000	0.0745	3.3623	3.6713
Opus	3	11.1099	3.7033	0.0277	0.0554	0.0745	3.5488	3.8578
PozzoSlag	3	12.6285	4.2095	0.0085	0.0170	0.0745	4.0550	4.3640
Slag	3	16.9446	5.6482	0.0341	0.0681	0.0745	5.4937	5.8027
Micron3+Marissa	3	10.4705	3.4902	0.0085	0.0170	0.0745	3.3357	3.6447
Liquid ASCM	3	13.4278	4.4759	0.0192	0.0383	0.0745	4.3214	4.6304

ANOVA								
Sources	*SS*	*df*	*MS*	*F*	*P value*	*Eta-sq*	*RMSSE*	*Omega Sq*
Between Groups	12.14683	10	1.214683	72.96047	1.6545E-14	0.970729	4.931547	0.956152
Within Groups	0.366267	22	0.0166					
Total	12.51309	32	0.3910					

TUKEY HSD/KRAMER			alpha	0.05	
group	*mean*	*n*	*ss*	*df*	*q-crit*
Control	4.2894	3	0.0554		
Elm Road	3.6767	3	0.0128		
Weston	4.2894	3	0.0554		
Reclaimed Ash	3.4902	3	0.0298		
Coal Creek	3.9697	3	0.0170		
Marissa	3.5168	3	0.0000		
Opus	3.7033	3	0.0554		
PozzoSlag	4.2095	3	0.0170		
Slag	5.6482	3	0.0681		
Micron3+Marissa	3.4902	3	0.0170		
Liquid ASCM	4.4759	3	0.0383		
		33	0.3663	22	5.056

Q TEST										
group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	*Statistical Significance*
Control	Elm Road	0.6128	0.0745	8.2257	0.2361	0.9894	0.0003	0.3766	4.7491	significant
Control	Weston	0.0000	0.0745	0.0000	-0.3766	0.3766	1.0000	0.3766	0.0000	not significant
Control	Reclaimed Ash	0.7993	0.0745	10.7292	0.4226	1.1759	0.0000	0.3766	6.1945	significant
Control	Coal Creek	0.3197	0.0745	4.2917	-0.0569	0.6964	0.1458	0.3766	2.4778	not significant
Control	Marissa	0.7726	0.0745	10.3716	0.3960	1.1493	0.0000	0.3766	5.9880	significant
Control	Opus	0.5861	0.0745	7.8681	0.2095	0.9628	0.0006	0.3766	4.5426	significant
Control	PozzoSlag	0.0799	0.0745	1.0729	-0.2967	0.4566	0.9993	0.3766	0.6195	not significant
Control	Slag	1.3588	0.0745	18.2397	0.9821	1.7354	0.0000	0.3766	10.5307	significant
Control	Micron3+Mariss	0.7993	0.0745	10.7292	0.4226	1.1759	0.0000	0.3766	6.1945	significant
Control	Liquid ASCM	0.1865	0.0745	2.5035	-0.1901	0.5631	0.7844	0.3766	1.4454	not significant

group 1	group 2	mean	std err	q-stat	lower	upper	p-value	mean-crit	Cohen d	Statistical Significance
Elm Road	Weston	0.6128	0.0745	8.2257	0.2361	0.9894	0.0003	0.3766	4.7491	significant
Elm Road	Reclaimed Ash	0.1865	0.0745	2.5035	-0.1901	0.5631	0.7844	0.3766	1.4454	not significant
Elm Road	Coal Creek	0.2931	0.0745	3.9340	-0.0836	0.6697	0.2280	0.3766	2.2713	not significant
Elm Road	Marissa	0.1599	0.0745	2.1458	-0.2168	0.5365	0.8987	0.3766	1.2389	not significant
Elm Road	Opus	0.0266	0.0745	0.3576	-0.3500	0.4033	1.0000	0.3766	0.2065	not significant
Elm Road	PozzoSlag	0.5328	0.0745	7.1528	0.1562	0.9095	0.0018	0.3766	4.1297	significant
Elm Road	Slag	1.9715	0.0745	26.4654	1.5949	2.3482	0.0000	0.3766	15.2798	significant
Elm Road	Micron3+Mariss	0.1865	0.0745	2.5035	-0.1901	0.5631	0.7844	0.3766	1.4454	not significant
Elm Road	Liquid ASCM	0.7993	0.0745	10.7292	0.4226	1.1759	0.0000	0.3766	6.1945	significant
Weston	Reclaimed Ash	0.7993	0.0745	10.7292	0.4226	1.1759	0.0000	0.3766	6.1945	significant
Weston	Coal Creek	0.3197	0.0745	4.2917	-0.0569	0.6964	0.1458	0.3766	2.4778	not significant
Weston	Marissa	0.7726	0.0745	10.3716	0.3960	1.1493	0.0000	0.3766	5.9880	significant
Weston	Opus	0.5861	0.0745	7.8681	0.2095	0.9628	0.0006	0.3766	4.5426	significant
Weston	PozzoSlag	0.0799	0.0745	1.0729	-0.2967	0.4566	0.9993	0.3766	0.6195	not significant
Weston	Slag	1.3588	0.0745	18.2397	0.9821	1.7354	0.0000	0.3766	10.5307	significant
Weston	Micron3+Mariss	0.7993	0.0745	10.7292	0.4226	1.1759	0.0000	0.3766	6.1945	significant
Weston	Liquid ASCM	0.1865	0.0745	2.5035	-0.1901	0.5631	0.7844	0.3766	1.4454	not significant
Reclaimed Ash	Coal Creek	0.4796	0.0745	6.4375	0.1029	0.8562	0.0058	0.3766	3.7167	significant
Reclaimed Ash	Marissa	0.0266	0.0745	0.3576	-0.3500	0.4033	1.0000	0.3766	0.2065	not significant
Reclaimed Ash	Opus	0.2131	0.0745	2.8611	-0.1635	0.5898	0.6366	0.3766	1.6519	not significant
Reclaimed Ash	PozzoSlag	0.7193	0.0745	9.6563	0.3427	1.0960	0.0000	0.3766	5.5751	significant
Reclaimed Ash	Slag	2.1580	0.0745	28.9689	1.7814	2.5347	0.0000	0.3766	16.7252	significant
Reclaimed Ash	Micron3+Mariss	0.0000	0.0745	0.0000	-0.3766	0.3766	1.0000	0.3766	0.0000	not significant
Reclaimed Ash	Liquid ASCM	0.9858	0.0745	13.2327	0.6091	1.3624	0.0000	0.3766	7.6399	significant

group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	*Statistical Significance*
Coal Creek	Marissa	0.4529	0.0745	6.0799	0.0763	0.8296	0.0102	0.3766	3.5102	significant
Coal Creek	Opus	0.2664	0.0745	3.5764	-0.1102	0.6431	0.3405	0.3766	2.0648	not significant
Coal Creek	PozzoSlag	0.2398	0.0745	3.2188	-0.1369	0.6164	0.4809	0.3766	1.8584	not significant
Coal Creek	Slag	1.6785	0.0745	22.5314	1.3018	2.0551	0.0000	0.3766	13.0085	significant
Coal Creek	Micron3+Mariss	0.4796	0.0745	6.4375	0.1029	0.8562	0.0058	0.3766	3.7167	significant
Coal Creek	Liquid ASCM	0.5062	0.0745	6.7952	0.1296	0.8829	0.0032	0.3766	3.9232	significant
Marissa	Opus	0.1865	0.0745	2.5035	-0.1901	0.5631	0.7844	0.3766	1.4454	not significant
Marissa	PozzoSlag	0.6927	0.0745	9.2987	0.3161	1.0694	0.0001	0.3766	5.3686	significant
Marissa	Slag	2.1314	0.0745	28.6113	1.7547	2.5080	0.0000	0.3766	16.5187	significant
Marissa	Micron3+Mariss	0.0266	0.0745	0.3576	-0.3500	0.4033	1.0000	0.3766	0.2065	not significant
Marissa	Liquid ASCM	0.9591	0.0745	12.8751	0.5825	1.3358	0.0000	0.3766	7.4334	significant
Opus	PozzoSlag	0.5062	0.0745	6.7952	0.1296	0.8829	0.0032	0.3766	3.9232	significant
Opus	Slag	1.9449	0.0745	26.1078	1.5683	2.3215	0.0000	0.3766	15.0733	significant
Opus	Micron3+Mariss	0.2131	0.0745	2.8611	-0.1635	0.5898	0.6366	0.3766	1.6519	not significant
Opus	Liquid ASCM	0.7726	0.0745	10.3716	0.3960	1.1493	0.0000	0.3766	5.9880	significant
PozzoSlag	Slag	1.4387	0.0745	19.3126	1.0620	1.8153	0.0000	0.3766	11.1501	significant
PozzoSlag	Micron3+Mariss	0.7193	0.0745	9.6563	0.3427	1.0960	0.0000	0.3766	5.5751	significant
PozzoSlag	Liquid ASCM	0.2664	0.0745	3.5764	-0.1102	0.6431	0.3405	0.3766	2.0648	not significant
Slag	Micron3+Mariss	2.1580	0.0745	28.9689	1.7814	2.5347	0.0000	0.3766	16.7252	significant
Slag	Liquid ASCM	1.1723	0.0745	15.7362	0.7956	1.5489	0.0000	0.3766	9.0853	significant
Micron3+Marissa	Liquid ASCM	0.9858	0.0745	13.2327	0.6091	1.3624	0.0000	0.3766	7.6399	significant

28 days

ANOVA: Single Factor

DESCRIPTION					Alpha	0.05		
Group	*Count*	*Sum*	*Mean*	*Variance*	*SS*	*Std Err*	*Lower*	*Upper*
Control	3	17.3442	5.7814	0.0085	0.0170	0.1150	5.5429	6.0199
Elm Road	3	21.7402	7.2467	0.1363	0.2726	0.1150	7.0082	7.4853
Weston	3	27.3351	9.1117	0.0000	0.0000	0.1150	8.8732	9.3502
Reclaimed Ash	3	21.1008	7.0336	0.0064	0.0128	0.1150	6.7951	7.2721
Coal Creek	3	22.6994	7.5665	0.0149	0.0298	0.1150	7.3279	7.8050
Marissa	3	18.3833	6.1278	0.0085	0.0170	0.1150	5.8892	6.3663
Opus	3	25.6567	8.5522	0.0447	0.0894	0.1150	8.3137	8.7908
PozzoSlag	3	27.1753	9.0584	0.0149	0.0298	0.1150	8.8199	9.2970
Slag	3	38.2852	12.7617	0.1299	0.2598	0.1150	12.5232	13.0003
Micron3+Marissa	3	22.6994	7.5665	0.0660	0.1320	0.1150	7.3279	7.8050
Liquid ASCM	3	17.7439	5.9146	0.0064	0.0128	0.1150	5.6761	6.1531

ANOVA								
Sources	*SS*	*df*	*MS*	*F*	*P value*	*Eta-sq*	*RMSSE*	*Omega Sq*
Between Groups	119.52	10	11.9520	301.1688	3.88E-21	0.9927	10.0195	0.9891
Within Groups	0.873079	22	0.0397					
Total	120.3931	32	3.7623					

TUKEY HSD/KRAMER			alpha	0.05	
group	*mean*	*n*	*ss*	*df*	*q-crit*
Control	5.7814	3	0.0170		
Elm Road	7.2467	3	0.2726		
Weston	9.1117	3	0.0000		
Reclaimed Ash	7.0336	3	0.0128		
Coal Creek	7.5665	3	0.0298		
Marissa	6.1278	3	0.0170		
Opus	8.5522	3	0.0894		
PozzoSlag	9.0584	3	0.0298		
Slag	12.7617	3	0.2598		
Micron3+Marissa	7.5665	3	0.1320		
Liquid ASCM	5.9146	3	0.0128		
		33	0.8731	22	5.056

group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	Statistical Significance
Control	Elm Road	1.4653	0.1150	12.7404	0.8838	2.0469	0.0000	0.5815	7.3557	significant
Control	Weston	3.3303	0.1150	28.9554	2.7488	3.9118	0.0000	0.5815	16.7174	significant
Control	Reclaimed Ash	1.2522	0.1150	10.8872	0.6707	1.8337	0.0000	0.5815	6.2857	significant
Control	Coal Creek	1.7850	0.1150	15.5201	1.2035	2.3666	0.0000	0.5815	8.9605	significant
Control	Marissa	0.3464	0.1150	3.0114	-0.2352	0.9279	0.5707	0.5815	1.7386	not significant
Control	Opus	2.7708	0.1150	24.0909	2.1893	3.3523	0.0000	0.5815	13.9089	significant
Control	PozzoSlag	3.2770	0.1150	28.4921	2.6955	3.8585	0.0000	0.5815	16.4499	significant
Control	Slag	6.9803	0.1150	60.6905	6.3988	7.5618	0.0000	0.5815	35.0397	significant
Control	Micron3+Marissa	1.7850	0.1150	15.5201	1.2035	2.3666	0.0000	0.5815	8.9605	significant
Control	Liquid ASCM	0.1332	0.1150	1.1582	-0.4483	0.7147	0.9987	0.5815	0.6687	not significant

group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	Statistical Significance
Elm Road	Weston	1.8650	0.1150	16.2150	1.2835	2.4465	0.0000	0.5815	9.3617	significant
Elm Road	Reclaimed Ash	0.2131	0.1150	1.8531	-0.3684	0.7947	0.9570	0.5815	1.0699	not significant
Elm Road	Coal Creek	0.3197	0.1150	2.7797	-0.2618	0.9012	0.6719	0.5815	1.6049	not significant
Elm Road	Marissa	1.1190	0.1150	9.7290	0.5375	1.7005	0.0000	0.5815	5.6170	significant
Elm Road	Opus	1.3055	0.1150	11.3505	0.7240	1.8870	0.0000	0.5815	6.5532	significant
Elm Road	PozzoSlag	1.8117	0.1150	15.7517	1.2302	2.3932	0.0000	0.5815	9.0943	significant
Elm Road	Slag	5.5150	0.1150	47.9501	4.9335	6.0965	0.0000	0.5815	27.6840	significant
Elm Road	Micron3+Marissa	0.3197	0.1150	2.7797	-0.2618	0.9012	0.6719	0.5815	1.6049	not significant
Elm Road	Liquid ASCM	1.3321	0.1150	11.5822	0.7506	1.9136	0.0000	0.5815	6.6870	significant
Weston	Reclaimed Ash	2.0781	0.1150	18.0682	1.4966	2.6596	0.0000	0.5815	10.4317	significant
Weston	Coal Creek	1.5453	0.1150	13.4353	0.9637	2.1268	0.0000	0.5815	7.7569	significant
Weston	Marissa	2.9840	0.1150	25.9440	2.4024	3.5655	0.0000	0.5815	14.9788	significant
Weston	Opus	0.5595	0.1150	4.8645	-0.0220	1.1410	0.0661	0.5815	2.8085	not significant
Weston	PozzoSlag	0.0533	0.1150	0.4633	-0.5282	0.6348	1.0000	0.5815	0.2675	not significant
Weston	Slag	3.6500	0.1150	31.7351	3.0685	4.2315	0.0000	0.5815	18.3223	significant
Weston	Micron3+Marissa	1.5453	0.1150	13.4353	0.9637	2.1268	0.0000	0.5815	7.7569	significant
Weston	Liquid ASCM	3.1971	0.1150	27.7972	2.6156	3.7786	0.0000	0.5815	16.0487	significant
Reclaimed Ash	Coal Creek	0.5328	0.1150	4.6329	-0.0487	1.1144	0.0919	0.5815	2.6748	not significant
Reclaimed Ash	Marissa	0.9058	0.1150	7.8759	0.3243	1.4874	0.0006	0.5815	4.5471	significant
Reclaimed Ash	Opus	1.5186	0.1150	13.2037	0.9371	2.1001	0.0000	0.5815	7.6231	significant
Reclaimed Ash	PozzoSlag	2.0248	0.1150	17.6049	1.4433	2.6063	0.0000	0.5815	10.1642	significant
Reclaimed Ash	Slag	5.7281	0.1150	49.8033	5.1466	6.3096	0.0000	0.5815	28.7539	significant
Reclaimed Ash	Micron3+Marissa	0.5328	0.1150	4.6329	-0.0487	1.1144	0.0919	0.5815	2.6748	not significant
Reclaimed Ash	Liquid ASCM	1.1190	0.1150	9.7290	0.5375	1.7005	0.0000	0.5815	5.6170	significant

group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	Statistical Significance
Coal Creek	Marissa	1.4387	0.1150	12.5087	0.8572	2.0202	0.0000	0.5815	7.2219	significant
Coal Creek	Opus	0.9858	0.1150	8.5708	0.4043	1.5673	0.0002	0.5815	4.9484	significant
Coal Creek	PozzoSlag	1.4920	0.1150	12.9720	0.9105	2.0735	0.0000	0.5815	7.4894	significant
Coal Creek	Slag	5.1953	0.1150	45.1704	4.6138	5.7768	0.0000	0.5815	26.0791	significant
Coal Creek	Micron3+Marissa	0.0000	0.1150	0.0000	-0.5815	0.5815	1.0000	0.5815	0.0000	not significant
Coal Creek	Liquid ASCM	1.6518	0.1150	14.3619	1.0703	2.2333	0.0000	0.5815	8.2918	significant
Marissa	Opus	2.4245	0.1150	21.0795	1.8429	3.0060	0.0000	0.5815	12.1703	significant
Marissa	PozzoSlag	2.9307	0.1150	25.4807	2.3492	3.5122	0.0000	0.5815	14.7113	significant
Marissa	Slag	6.6340	0.1150	57.6791	6.0525	7.2155	0.0000	0.5815	33.3011	significant
Marissa	Micron3+Marissa	1.4387	0.1150	12.5087	0.8572	2.0202	0.0000	0.5815	7.2219	significant
Marissa	Liquid ASCM	0.2131	0.1150	1.8531	-0.3684	0.7947	0.9570	0.5815	1.0699	not significant
Opus	PozzoSlag	0.5062	0.1150	4.4012	-0.0753	1.0877	0.1261	0.5815	2.5410	not significant
Opus	Slag	4.2095	0.1150	36.5996	3.6280	4.7910	0.0000	0.5815	21.1308	significant
Opus	Micron3+Marissa	0.9858	0.1150	8.5708	0.4043	1.5673	0.0002	0.5815	4.9484	significant
Opus	Liquid ASCM	2.6376	0.1150	22.9327	2.0561	3.2191	0.0000	0.5815	13.2402	significant
PozzoSlag	Slag	3.7033	0.1150	32.1984	3.1218	4.2848	0.0000	0.5815	18.5898	significant
PozzoSlag	Micron3+Marissa	1.4920	0.1150	12.9720	0.9105	2.0735	0.0000	0.5815	7.4894	significant
PozzoSlag	Liquid ASCM	3.1438	0.1150	27.3339	2.5623	3.7253	0.0000	0.5815	15.7812	significant
Slag	Micron3+Marissa	5.1953	0.1150	45.1704	4.6138	5.7768	0.0000	0.5815	26.0791	significant
Slag	Liquid ASCM	6.8471	0.1150	59.5323	6.2656	7.4286	0.0000	0.5815	34.3710	significant
Micron3+Marissa	Liquid ASCM	1.6518	0.1150	14.3619	1.0703	2.2333	0.0000	0.5815	8.2918	significant

90 days

ANOVA: Single Factor

DESCRIPTION					Alpha	0.05		
Group	*Count*	*Sum*	*Mean*	*Variance*	*SS*	*Std Err*	*Lower*	*Upper*
Control	3	22.7793	7.5931	0.5175	1.0349	0.1930	7.1929	7.9933
Elm Road	3	44.5195	14.8398	0.0277	0.0554	0.1930	14.4397	15.2400
Weston	3	50.6739	16.8913	0.0405	0.0809	0.1930	16.4911	17.2915
Reclaimed Ash	3	35.5677	11.8559	0.0277	0.0554	0.1930	11.4557	12.2561
Coal Creek	3	48.8356	16.2785	0.0277	0.0554	0.1930	15.8784	16.6787
Marissa	3	47.9564	15.9855	0.0447	0.0894	0.1930	15.5853	16.3856
Opus	3	72.0145	24.0048	0.0660	0.1320	0.1930	23.6047	24.4050
PozzoSlag	3	50.8338	16.9446	0.0447	0.0894	0.1930	16.5444	17.3448
Slag	3	51.0736	17.0245	0.1342	0.2683	0.1930	16.6244	17.4247
Micron3+Marissa	3	61.3043	20.4348	0.2385	0.4770	0.1930	20.0346	20.8349
Liquid ASCM	3	24.7775	8.2592	0.0596	0.1192	0.1930	7.8590	8.6593

ANOVA								
Sources	*SS*	*df*	*MS*	*F*	*P value*	*Eta-sq*	*RMSSE*	*Omega Sq*
Between Groups	697.57	10	69.7570	624.5040	1.34E-24	0.9965	14.4280	0.9947
Within Groups	2.457397	22	0.1117					
Total	700.0274	32	21.8759					

TUKEY HSD/KRAMER			alpha	0.05	
group	*mean*	*n*	*ss*	*df*	*q-crit*
Control	7.5931	3	1.0349		
Elm Road	14.8398	3	0.0554		
Weston	16.8913	3	0.0809		
Reclaimed Ash	11.8559	3	0.0554		
Coal Creek	16.2785	3	0.0554		
Marissa	15.9855	3	0.0894		
Opus	24.0048	3	0.1320		
PozzoSlag	16.9446	3	0.0894		
Slag	17.0245	3	0.2683		
Micron3+Marissa	20.4348	3	0.4770		
Liquid ASCM	8.2592	3	0.1192		
		33	2.4574	22	5.056

Q TEST										
group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	Statistical Significance
Control	Elm Road	7.2467	0.1930	37.5558	6.2711	8.2223	0.0000	0.9756	21.6829	significant
Control	Weston	9.2982	0.1930	48.1874	8.3226	10.2738	0.0000	0.9756	27.8210	significant
Control	Reclaimed Ash	4.2628	0.1930	22.0917	3.2872	5.2384	0.0000	0.9756	12.7546	significant
Control	Coal Creek	8.6854	0.1930	45.0118	7.7098	9.6610	0.0000	0.9756	25.9876	significant
Control	Marissa	8.3924	0.1930	43.4930	7.4168	9.3680	0.0000	0.9756	25.1107	significant
Control	Opus	16.4117	0.1930	85.0529	15.4361	17.3873	0.0000	0.9756	49.1053	significant
Control	PozzoSlag	9.3515	0.1930	48.4636	8.3759	10.3271	0.0000	0.9756	27.9805	significant
Control	Slag	9.4314	0.1930	48.8778	8.4558	10.4070	0.0000	0.9756	28.2196	significant
Control	Micron3+Marissa	12.8417	0.1930	66.5511	11.8661	13.8173	0.0000	0.9756	38.4233	significant
Control	Liquid ASCM	0.6661	0.1930	3.4518	-0.3095	1.6417	0.3866	0.9756	1.9929	not significan

group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	Statistical Significance
Elm Road	Weston	2.0515	0.1930	10.6316	1.0759	3.0271	0.0000	0.9756	6.1382	significant
Elm Road	Reclaimed Ash	2.9840	0.1930	15.4642	2.0084	3.9596	0.0000	0.9756	8.9282	significant
Elm Road	Coal Creek	1.4387	0.1930	7.4559	0.4631	2.4143	0.0011	0.9756	4.3047	significant
Elm Road	Marissa	1.1456	0.1930	5.9371	0.1700	2.1212	0.0129	0.9756	3.4278	significant
Elm Road	Opus	9.1650	0.1930	47.4971	8.1894	10.1406	0.0000	0.9756	27.4224	significant
Elm Road	PozzoSlag	2.1048	0.1930	10.9078	1.1292	3.0804	0.0000	0.9756	6.2976	significant
Elm Road	Slag	2.1847	0.1930	11.3220	1.2091	3.1603	0.0000	0.9756	6.5367	significant
Elm Road	Micron3+Marissa	5.5949	0.1930	28.9953	4.6193	6.5705	0.0000	0.9756	16.7404	significant
Elm Road	Liquid ASCM	6.5807	0.1930	34.1040	5.6051	7.5563	0.0000	0.9756	19.6900	significant
Weston	Reclaimed Ash	5.0354	0.1930	26.0958	4.0598	6.0110	0.0000	0.9756	15.0664	significant
Weston	Coal Creek	0.6128	0.1930	3.1757	-0.3628	1.5884	0.4992	0.9756	1.8335	not significant
Weston	Marissa	0.9058	0.1930	4.6945	-0.0698	1.8814	0.0843	0.9756	2.7104	not significant
Weston	Opus	7.1135	0.1930	36.8655	6.1379	8.0891	0.0000	0.9756	21.2843	significant
Weston	PozzoSlag	0.0533	0.1930	0.2761	-0.9223	1.0289	1.0000	0.9756	0.1594	not significant
Weston	Slag	0.1332	0.1930	0.6904	-0.8424	1.1088	1.0000	0.9756	0.3986	not significant
Weston	Micron3+Marissa	3.5434	0.1930	18.3637	2.5678	4.5190	0.0000	0.9756	10.6023	significant
Weston	Liquid ASCM	8.6322	0.1930	44.7356	7.6566	9.6078	0.0000	0.9756	25.8281	significant
Reclaimed Ash	Coal Creek	4.4226	0.1930	22.9201	3.4470	5.3982	0.0000	0.9756	13.2329	significant
Reclaimed Ash	Marissa	4.1296	0.1930	21.4013	3.1540	5.1052	0.0000	0.9756	12.3560	significant
Reclaimed Ash	Opus	12.1490	0.1930	62.9612	11.1734	13.1246	0.0000	0.9756	36.3507	significant
Reclaimed Ash	PozzoSlag	5.0887	0.1930	26.3719	4.1131	6.0643	0.0000	0.9756	15.2258	significant
Reclaimed Ash	Slag	5.1686	0.1930	26.7861	4.1930	6.1442	0.0000	0.9756	15.4650	significant
Reclaimed Ash	Micron3+Marissa	8.5789	0.1930	44.4595	7.6033	9.5545	0.0000	0.9756	25.6687	significant
Reclaimed Ash	Liquid ASCM	3.5967	0.1930	18.6398	2.6211	4.5723	0.0000	0.9756	10.7617	significant

group 1	group 2	mean	std err	q-stat	lower	upper	p-value	mean-crit	Cohen d	Statistical Significance
Coal Creek	Marissa	0.2931	0.1930	1.5188	-0.6825	1.2687	0.9889	0.9756	0.8769	not significant
Coal Creek	Opus	7.7263	0.1930	40.0411	6.7507	8.7019	0.0000	0.9756	23.1178	significant
Coal Creek	PozzoSlag	0.6661	0.1930	3.4518	-0.3095	1.6417	0.3866	0.9756	1.9929	not significant
Coal Creek	Slag	0.7460	0.1930	3.8660	-0.2296	1.7216	0.2470	0.9756	2.2321	not significant
Coal Creek	Micron3+Marissa	4.1562	0.1930	21.5394	3.1806	5.1318	0.0000	0.9756	12.4358	significant
Coal Creek	Liquid ASCM	8.0194	0.1930	41.5599	7.0438	8.9950	0.0000	0.9756	23.9946	significant
Marissa	Opus	8.0194	0.1930	41.5599	7.0438	8.9950	0.0000	0.9756	23.9946	significant
Marissa	PozzoSlag	0.9591	0.1930	4.9706	-0.0165	1.9347	0.0567	0.9756	2.8698	not significant
Marissa	Slag	1.0391	0.1930	5.3848	0.0635	2.0147	0.0304	0.9756	3.1089	significant
Marissa	Micron3+Marissa	4.4493	0.1930	23.0582	3.4737	5.4249	0.0000	0.9756	13.3126	significant
Marissa	Liquid ASCM	7.7263	0.1930	40.0411	6.7507	8.7019	0.0000	0.9756	23.1178	significant
Opus	PozzoSlag	7.0602	0.1930	36.5893	6.0846	8.0359	0.0000	0.9756	21.1249	significant
Opus	Slag	6.9803	0.1930	36.1751	6.0047	7.9559	0.0000	0.9756	20.8857	significant
Opus	Micron3+Marissa	3.5701	0.1930	18.5018	2.5945	4.5457	0.0000	0.9756	10.6820	significant
Opus	Liquid ASCM	15.7457	0.1930	81.6011	14.7701	16.7213	0.0000	0.9756	47.1124	significant
PozzoSlag	Slag	0.0799	0.1930	0.4142	-0.8957	1.0555	1.0000	0.9756	0.2391	not significant
PozzoSlag	Micron3+Marissa	3.4902	0.1930	18.0875	2.5146	4.4658	0.0000	0.9756	10.4429	significant
PozzoSlag	Liquid ASCM	8.6854	0.1930	45.0118	7.7098	9.6610	0.0000	0.9756	25.9876	significant
Slag	Micron3+Marissa	3.4102	0.1930	17.6733	2.4346	4.3858	0.0000	0.9756	10.2037	significant
Slag	Liquid ASCM	8.7654	0.1930	45.4260	7.7898	9.7410	0.0000	0.9756	26.2267	significant
Micron3+Marissa	Liquid ASCM	12.1756	0.1930	63.0993	11.2000	13.1512	0.0000	0.9756	36.4304	significant

180 days

ANOVA: Single Factor

DESCRIPTION					Alpha	0.05		
Group	*Count*	*Sum*	*Mean*	*Variance*	*SS*	*Std Err*	*Lower*	*Upper*
Control	3	26.8556	8.9519	0.0575	0.1150	0.3058	8.3177	9.5860
Elm Road	3	63.6222	21.2074	0.1555	0.3109	0.3058	20.5732	21.8415
Weston	3	71.3751	23.7917	0.2193	0.4387	0.3058	23.1576	24.4259
Reclaimed Ash	3	47.7166	15.9055	0.0575	0.1150	0.3058	15.2714	16.5397
Coal Creek	3	75.4514	25.1505	1.1904	2.3807	0.3058	24.5163	25.7846
Marissa	3	83.3642	27.7881	0.5132	1.0264	0.3058	27.1539	28.4222
Opus	3	124.3669	41.4556	0.1938	0.3876	0.3058	40.8215	42.0898
PozzoSlag	3	76.4105	25.4702	0.3854	0.7709	0.3058	24.8360	26.1043
Slag	3	59.6258	19.8753	0.0788	0.1576	0.3058	19.2411	20.5094
Micron3+Marissa	3	115.9746	38.6582	0.0916	0.1831	0.3058	38.0240	39.2923
Liquid ASCM	3	28.2144	9.4048	0.1427	0.2853	0.3058	8.7706	10.0389

ANOVA								
Sources	*SS*	*df*	*MS*	*F*	*P value*	*Eta-sq*	*RMSSE*	*Omega Sq*
Between Groups	3190.752	10	319.0752	1137.4908	1.88E-27	0.9981	19.4721	0.9971
Within Groups	6.171175	22	0.2805					
Total	3196.923	32	99.9038					

TUKEY HSD/KRAMER			alpha	0.05	
group	*mean*	*n*	*ss*	*df*	*q-crit*
Control	8.9519	3	0.1150		
Elm Road	21.2074	3	0.3109		
Weston	23.7917	3	0.4387		
Reclaimed Ash	15.9055	3	0.1150		
Coal Creek	25.1505	3	2.3807		
Marissa	27.7881	3	1.0264		
Opus	41.4556	3	0.3876		
PozzoSlag	25.4702	3	0.7709		
Slag	19.8753	3	0.1576		
Micron3+Marissa	38.6582	3	0.1831		
Liquid ASCM	9.4048	3	0.2853		
		33	6.1712	22	5.056

Q TEST										
group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	Statistical Significance
Control	Elm Road	12.2555	0.3058	40.0793	10.7095	13.8016	0.0000	1.5460	23.1398	significant
Control	Weston	14.8398	0.3058	48.5308	13.2938	16.3859	0.0000	1.5460	28.0193	significant
Control	Reclaimed Ash	6.9537	0.3058	22.7406	5.4076	8.4997	0.0000	1.5460	13.1293	significant
Control	Coal Creek	16.1986	0.3058	52.9744	14.6526	17.7446	0.0000	1.5460	30.5848	significant
Control	Marissa	18.8362	0.3058	61.6001	17.2902	20.3822	0.0000	1.5460	35.5648	significant
Control	Opus	32.5038	0.3058	106.2972	30.9578	34.0498	0.0000	1.5460	61.3707	significant
Control	PozzoSlag	16.5183	0.3058	54.0199	14.9723	18.0644	0.0000	1.5460	31.1884	significant
Control	Slag	10.9234	0.3058	35.7228	9.3774	12.4694	0.0000	1.5460	20.6246	significant
Control	Micron3+Marissa	29.7063	0.3058	97.1487	28.1603	31.2524	0.0000	1.5460	56.0888	significant
Control	Liquid ASCM	0.4529	0.3058	1.4812	-1.0931	1.9990	0.9908	1.5460	0.8552	not significant

group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	Statistical Significance
Elm Road	Weston	2.5843	0.3058	8.4515	1.0383	4.1304	0.0002	1.5460	4.8795	significant
Elm Road	Reclaimed Ash	5.3018	0.3058	17.3386	3.7558	6.8479	0.0000	1.5460	10.0105	significant
Elm Road	Coal Creek	3.9431	0.3058	12.8951	2.3970	5.4891	0.0000	1.5460	7.4450	significant
Elm Road	Marissa	6.5807	0.3058	21.5208	5.0347	8.1267	0.0000	1.5460	12.4251	significant
Elm Road	Opus	20.2483	0.3058	66.2180	18.7022	21.7943	0.0000	1.5460	38.2310	significant
Elm Road	PozzoSlag	4.2628	0.3058	13.9406	2.7168	5.8088	0.0000	1.5460	8.0486	significant
Elm Road	Slag	1.3321	0.3058	4.3564	-0.2139	2.8782	0.1339	1.5460	2.5152	not significant
Elm Road	Micron3+Marissa	17.4508	0.3058	57.0694	15.9048	18.9968	0.0000	1.5460	32.9490	significant
Elm Road	Liquid ASCM	11.8026	0.3058	38.5981	10.2566	13.3486	0.0000	1.5460	22.2846	significant
Weston	Reclaimed Ash	7.8862	0.3058	25.7901	6.3401	9.4322	0.0000	1.5460	14.8899	significant
Weston	Coal Creek	1.3588	0.3058	4.4436	-0.1873	2.9048	0.1192	1.5460	2.5655	not significant
Weston	Marissa	3.9964	0.3058	13.0693	2.4503	5.5424	0.0000	1.5460	7.5456	significant
Weston	Opus	17.6639	0.3058	57.7664	16.1179	19.2100	0.0000	1.5460	33.3515	significant
Weston	PozzoSlag	1.6785	0.3058	5.4891	0.1324	3.2245	0.0259	1.5460	3.1691	significant
Weston	Slag	3.9164	0.3058	12.8079	2.3704	5.4625	0.0000	1.5460	7.3947	significant
Weston	Micron3+Marissa	14.8665	0.3058	48.6179	13.3205	16.4125	0.0000	1.5460	28.0696	significant
Weston	Liquid ASCM	14.3869	0.3058	47.0496	12.8409	15.9330	0.0000	1.5460	27.1641	significant
Reclaimed Ash	Coal Creek	9.2449	0.3058	30.2337	7.6989	10.7910	0.0000	1.5460	17.4554	significant
Reclaimed Ash	Marissa	11.8825	0.3058	38.8595	10.3365	13.4286	0.0000	1.5460	22.4355	significant
Reclaimed Ash	Opus	25.5501	0.3058	83.5566	24.0041	27.0961	0.0000	1.5460	48.2414	significant
Reclaimed Ash	PozzoSlag	9.5646	0.3058	31.2793	8.0186	11.1107	0.0000	1.5460	18.0591	significant
Reclaimed Ash	Slag	3.9697	0.3058	12.9822	2.4237	5.5158	0.0000	1.5460	7.4953	significant
Reclaimed Ash	Micron3+Marissa	22.7526	0.3058	74.4081	21.2066	24.2987	0.0000	1.5460	42.9595	significant
Reclaimed Ash	Liquid ASCM	6.5008	0.3058	21.2594	4.9547	8.0468	0.0000	1.5460	12.2741	significant

group 1	group 2	mean	std err	q-stat	lower	upper	p-value	mean-crit	Cohen d	Statistical Significance
Coal Creek	Marissa	2.6376	0.3058	8.6258	1.0916	4.1836	0.0002	1.5460	4.9801	significant
Coal Creek	Opus	16.3052	0.3058	53.3229	14.7591	17.8512	0.0000	1.5460	30.7860	significant
Coal Creek	PozzoSlag	0.3197	0.3058	1.0455	-1.2263	1.8657	0.9994	1.5460	0.6036	not significant
Coal Creek	Slag	5.2752	0.3058	17.2515	3.7292	6.8212	0.0000	1.5460	9.9602	significant
Coal Creek	Micron3+Marissa	13.5077	0.3058	44.1743	11.9617	15.0538	0.0000	1.5460	25.5041	significant
Coal Creek	Liquid ASCM	15.7457	0.3058	51.4932	14.1997	17.2917	0.0000	1.5460	29.7296	significant
Marissa	Opus	13.6676	0.3058	44.6971	12.1215	15.2136	0.0000	1.5460	25.8059	significant
Marissa	PozzoSlag	2.3179	0.3058	7.5802	0.7719	3.8639	0.0009	1.5460	4.3764	significant
Marissa	Slag	7.9128	0.3058	25.8773	6.3668	9.4588	0.0000	1.5460	14.9403	significant
Marissa	Micron3+Marissa	10.8701	0.3058	35.5486	9.3241	12.4162	0.0000	1.5460	20.5240	significant
Marissa	Liquid ASCM	18.3833	0.3058	60.1189	16.8373	19.9293	0.0000	1.5460	34.7097	significant
Opus	PozzoSlag	15.9855	0.3058	52.2773	14.4394	17.5315	0.0000	1.5460	30.1823	significant
Opus	Slag	21.5804	0.3058	70.5744	20.0343	23.1264	0.0000	1.5460	40.7461	significant
Opus	Micron3+Marissa	2.7975	0.3058	9.1485	1.2514	4.3435	0.0001	1.5460	5.2819	significant
Opus	Liquid ASCM	32.0509	0.3058	104.8160	30.5048	33.5969	0.0000	1.5460	60.5156	significant
PozzoSlag	Slag	5.5949	0.3058	18.2971	4.0489	7.1409	0.0000	1.5460	10.5638	significant
PozzoSlag	Micron3+Marissa	13.1880	0.3058	43.1288	11.6420	14.7340	0.0000	1.5460	24.9004	significant
PozzoSlag	Liquid ASCM	16.0654	0.3058	52.5387	14.5194	17.6114	0.0000	1.5460	30.3332	significant
Slag	Micron3+Marissa	18.7829	0.3058	61.4259	17.2369	20.3290	0.0000	1.5460	35.4642	significant
Slag	Liquid ASCM	10.4705	0.3058	34.2417	8.9244	12.0165	0.0000	1.5460	19.7694	significant
Micron3+Marissa	Liquid ASCM	29.2534	0.3058	95.6675	27.7074	30.7994	0.0000	1.5460	55.2337	significant

Shrinkage

ANOVA: Single Factor

DESCRIPTION					Alpha	0.05		
Group	*Count*	*Sum*	*Mean*	*Variance*	*SS*	*Std Err*	*Lower*	*Upper*
Marissa	3	-0.11925	-0.03975	1.64E-05	3.28E-05	0.00167	-0.04321	-0.03629
Elm Road	3	-0.11837	-0.03946	3.38E-06	6.76E-06	0.00167	-0.04292	-0.03599
OPUS	3	-0.12000	-0.04000	1.00E-06	2.00E-06	0.00167	-0.04346	-0.03654
Micron+Marissa	3	-0.12500	-0.04167	2.13E-05	4.27E-05	0.00167	-0.04513	-0.03820
Coal Creek	3	-0.12367	-0.04122	2.60E-07	5.20E-07	0.00167	-0.04469	-0.03776
PozzoSlag	3	-0.12100	-0.04033	9.33E-06	1.87E-05	0.00167	-0.04380	-0.03687
Slag	3	-0.13000	-0.04333	2.63E-05	5.27E-05	0.00167	-0.04680	-0.03987
Weston	3	-0.11300	-0.03767	3.33E-07	6.67E-07	0.00167	-0.04113	-0.03420
Control	3	-0.07700	-0.02567	3.33E-07	6.67E-07	0.00167	-0.02913	-0.02220
Reclaimed	3	-0.15100	-0.05033	1.23E-05	2.47E-05	0.00167	-0.05380	-0.04687
LASCM	3	-0.09000	-0.03000	1.00E-06	2.00E-06	0.00167	-0.03346	-0.02654

Sources	*SS*	*df*	*MS*	*F*	*P value*	*Eta-sq*	*RMSSE*	*Omega Sq*
Between Groups	0.00127	10	0.00013	15.18119	1.11E-07	0.87343	2.24953	0.81123
Within Groups	0.000184	22	8.37E-06					
Total	0.001454	32	4.54E-05					

TUKEY HSD/KRAMER			alpha	0.05	
group	*mean*	*n*	*ss*	*df*	*q-crit*
Marissa	-0.03975	3	3.28E-05		
Elm Road	-0.03946	3	6.76E-06		
OPUS	-0.04000	3	2.00E-06		
Micron+Marissa	-0.04167	3	4.27E-05		
Coal Creek	-0.04122	3	5.20E-07		
PozzoSlag	-0.04033	3	1.87E-05		
Slag	-0.04333	3	5.27E-05		
Weston	-0.03767	3	6.67E-07		
Control	-0.02567	3	6.67E-07		
Reclaimed	-0.05033	3	2.47E-05		
LASCM	-0.03000	3	2.00E-06		
		33	0.000184	22	5.056

group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*	*Statistical Significance*
Marissa	Elm Road	0.00029	0.00167	0.17632	-0.00815	0.00874	1.00000	0.00844	0.10180	not significant
Marissa	OPUS	0.00025	0.00167	0.14980	-0.00819	0.00869	1.00000	0.00844	0.08648	not significant
Marissa	Micron+Marissa	0.00192	0.00167	1.14784	-0.00653	0.01036	0.99876	0.00844	0.66270	not significant
Marissa	Coal Creek	0.00147	0.00167	0.88160	-0.00697	0.00992	0.99987	0.00844	0.50899	not significant
Marissa	PozzoSlag	0.00058	0.00167	0.34940	-0.00786	0.00903	1.00000	0.00844	0.20173	not significant
Marissa	Slag	0.00358	0.00167	2.14588	-0.00486	0.01203	0.89865	0.00844	1.23892	not significant
Marissa	Weston	0.00208	0.00167	1.24746	-0.00636	0.01053	0.99756	0.00844	0.72022	not significant
Marissa	Control	0.01408	0.00167	8.43335	0.00564	0.02253	0.00023	0.00844	4.86900	significant
Marissa	Reclaimed	0.01058	0.00167	6.33765	0.00214	0.01903	0.00677	0.00844	3.65904	significant
Marissa	LASCM	0.00975	0.00167	5.83845	0.00131	0.01819	0.01503	0.00844	3.37083	significant

group 1	*group 2*	*mean*	*std err*	*q-stat*	*lower*	*upper*	*p-value*	*mean-crit*	*Cohen d*		*Statistical Significance*
Elm Road	OPUS	0.00054	0.00167	0.32612	-0.00790	0.00899	1.00000	0.00844	0.18828		not significant
Elm Road	Micron+Marissa	0.00221	0.00167	1.32416	-0.00623	0.01065	0.99607	0.00844	0.76450		not significant
Elm Road	Coal Creek	0.00177	0.00167	1.05792	-0.00668	0.01021	0.99938	0.00844	0.61079		not significant
Elm Road	PozzoSlag	0.00088	0.00167	0.52572	-0.00757	0.00932	1.00000	0.00844	0.30353		not significant
Elm Road	Slag	0.00388	0.00167	2.32220	-0.00457	0.01232	0.84782	0.00844	1.34072		not significant
Elm Road	Weston	0.00179	0.00167	1.07114	-0.00665	0.01023	0.99931	0.00844	0.61842		not significant
Elm Road	Control	0.01379	0.00167	8.25703	0.00535	0.02223	0.00030	0.00844	4.76720		significant
Elm Road	Reclaimed	0.01088	0.00167	6.51397	0.00243	0.01932	0.00510	0.00844	3.76084		significant
Elm Road	LASCM	0.00946	0.00167	5.66213	0.00101	0.01790	0.01983	0.00844	3.26903		significant
OPUS	Micron+Marissa	0.00167	0.00167	0.99804	-0.00678	0.01011	0.99962	0.00844	0.57622		not significant
OPUS	Coal Creek	0.00122	0.00167	0.73180	-0.00722	0.00967	0.99998	0.00844	0.42251		not significant
OPUS	PozzoSlag	0.00033	0.00167	0.19961	-0.00811	0.00878	1.00000	0.00844	0.11524		not significant
OPUS	Slag	0.00333	0.00167	1.99608	-0.00511	0.01178	0.93257	0.00844	1.15244		not significant
OPUS	Weston	0.00233	0.00167	1.39726	-0.00611	0.01078	0.99405	0.00844	0.80671		not significant
OPUS	Control	0.01433	0.00167	8.58315	0.00589	0.02278	0.00018	0.00844	4.95548		significant
OPUS	Reclaimed	0.01033	0.00167	6.18785	0.00189	0.01878	0.00862	0.00844	3.57256		significant
OPUS	LASCM	0.01000	0.00167	5.98824	0.00156	0.01844	0.01186	0.00844	3.45731		significant
Micron+Marissa	Coal Creek	0.00044	0.00167	0.26624	-0.00800	0.00889	1.00000	0.00844	0.15371		not significant
Micron+Marissa	PozzoSlag	0.00133	0.00167	0.79843	-0.00711	0.00978	0.99995	0.00844	0.46098		not significant
Micron+Marissa	Slag	0.00167	0.00167	0.99804	-0.00678	0.01011	0.99962	0.00844	0.57622		not significant
Micron+Marissa	Weston	0.00400	0.00167	2.39530	-0.00444	0.01244	0.82350	0.00844	1.38293		not significant
Micron+Marissa	Control	0.01600	0.00167	9.58119	0.00756	0.02444	0.00004	0.00844	5.53170		significant
Micron+Marissa	Reclaimed	0.00867	0.00167	5.18981	0.00022	0.01711	0.04093	0.00844	2.99634		significant
Micron+Marissa	LASCM	0.01167	0.00167	6.98628	0.00322	0.02011	0.00237	0.00844	4.03353		significant

group 1	group 2	mean	std err	q-stat	lower	upper	p-value	mean-crit	Cohen d	Statistical Significance
Coal Creek	PozzoSlag	0.00089	0.00167	0.53220	-0.00755	0.00933	1.00000	0.00844	0.30726	not significant
Coal Creek	Slag	0.00211	0.00167	1.26428	-0.00633	0.01055	0.99728	0.00844	0.72993	not significant
Coal Creek	Weston	0.00356	0.00167	2.12906	-0.00489	0.01200	0.90289	0.00844	1.22921	not significant
Coal Creek	Control	0.01556	0.00167	9.31495	0.00711	0.02400	0.00006	0.00844	5.37799	significant
Coal Creek	Reclaimed	0.00911	0.00167	5.45605	0.00067	0.01755	0.02730	0.00844	3.15005	significant
Coal Creek	LASCM	0.01122	0.00167	6.72005	0.00278	0.01967	0.00365	0.00844	3.87982	significant
PozzoSlag	Slag	0.00300	0.00167	1.79647	-0.00544	0.01144	0.96476	0.00844	1.03719	not significant
PozzoSlag	Weston	0.00267	0.00167	1.59686	-0.00578	0.01111	0.98410	0.00844	0.92195	not significant
PozzoSlag	Control	0.01467	0.00167	8.78276	0.00622	0.02311	0.00013	0.00844	5.07073	significant
PozzoSlag	Reclaimed	0.01000	0.00167	5.98824	0.00156	0.01844	0.01186	0.00844	3.45731	significant
PozzoSlag	LASCM	0.01033	0.00167	6.18785	0.00189	0.01878	0.00862	0.00844	3.57256	significant
Slag	Weston	0.00567	0.00167	3.39334	-0.00278	0.01411	0.40940	0.00844	1.95914	not significant
Slag	Control	0.01767	0.00167	10.57923	0.00922	0.02611	0.00001	0.00844	6.10792	significant
Slag	Reclaimed	0.00700	0.00167	4.19177	-0.00144	0.01544	0.16587	0.00844	2.42012	not significant
Slag	LASCM	0.01333	0.00167	7.98432	0.00489	0.02178	0.00047	0.00844	4.60975	significant
Weston	Control	0.01200	0.00167	7.18589	0.00356	0.02044	0.00171	0.00844	4.14878	significant
Weston	Reclaimed	0.01267	0.00167	7.58511	0.00422	0.02111	0.00089	0.00844	4.37926	significant
Weston	LASCM	0.00767	0.00167	4.59099	-0.00078	0.01611	0.09741	0.00844	2.65061	not significant
Control	Reclaimed	0.02467	0.00167	14.77100	0.01622	0.03311	0.00000	0.00844	8.52804	significant
Control	LASCM	0.00433	0.00167	2.59491	-0.00411	0.01278	0.74889	0.00844	1.49817	not significant
Reclaimed	LASCM	0.02033	0.00167	12.17609	0.01189	0.02878	0.00000	0.00844	7.02987	significant