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RESEARCH REPORT

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## RP271

# Implementing AASHTO TP 110 for Alkali-Silica Reaction Potential Evaluation of Idaho Aggregates

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16. Abstract

Alkali-Silica Reaction (ASR) has been recognized as a major distress in concrete for over a century. In the United States, ASR is a major cause of the deterioration of highway concrete structures. In Idaho, several aggregate sources have been reported to be ASR-susceptible. The primary objective of the current research study was to evaluate the advantages associated with implementing AASHTO TP-110 (Miniature Concrete Prism Test, [MCPT]) within ITD specifications to characterize the ASR susceptibility of Idaho aggregates. This test method has been recently adopted by AASHTO as T 380. In this research study, a total of 14 different aggregate materials (both coarse and fine fractions), including a non-reactive reference aggregate, were collected from various sources across and adjacent to Idaho, and were tested using the 56-days MCPT as well as the commonly used Accelerated Mortar Bar Test (AMBT; ASTM C 1260). Additionally, the 1-year Concrete Prism Test (CPT; ASTM C 1293) was carried out on selected aggregates. Finally, a shortened version of the ASTM C 1293 test was also explored to assess its suitability for application.

The results demonstrated that all aggregate materials (both coarse and fine fractions) tested in the current study were ASR-susceptible. Overall, the MCPT results were found to correlate well with the 14-day AMBT test results. As all the aggregate materials were found to be ASR-susceptible, no instance of false-positive or false-negative results were encountered in the current study. Although the results from this new method were found to be consistent with the other methods (in terms of deciding whether a particular aggregate was reactive or not), better evaluation of the test method will be possible only when the results are compared against field performance of aggregates. The study therefore recommends the Idaho Transportation Department (ITD) to initiate other studies where the laboratory test results can be compared with field performance of aggregates in terms of ASR susceptibility. Moreover, these studies should focus on testing both reactive as well as non-reactive aggregates.

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|---|---|---|---|---|---|---|---|---|---|
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| | | LENGTH | | | | | LENGTH | | |
| in | inches | 25.4 | millimeters | mm | mm | millimeters | 0.039 | inches | in |
| ft | feet | 0.3048 | meters | m | m | meters | 3.28 | feet | ft |
| yd | yards | 0.914 | meters | m | m | meters | 1.09 | yards | yd |
| mi | miles (statute) | 1.61 | kilometers | km | km | kilometers | 0.621 | miles (statute) | mi |
| | | AREA | | | | | AREA | | |
| $in^2$ | square inches | 645.2 | millimeters squared | $cm^2$ | $mm^2$ | millimeters squared | 0.0016 | square inches | $in^2$ |
| $ft^2$ | square feet | 0.0929 | meters squared | $m^2$ | $m^2$ | meters squared | 10.764 | square feet | $ft^2$ |
| $yd^2$ | square yards | 0.836 | meters squared | $m^2$ | $km^2$ | kilometers squared | 0.39 | square miles | $mi^2$ |
| $mi^2$ | square miles | 2.59 | kilometers squared | $km^2$ | ha | hectares (10,000 $m^2$) | 2.471 | acres | ac |
| ac | acres | 0.4046 | hectares | ha | | | | | |
| | | MASS (weight) | | | | | MASS (weight) | | |
| oz | Ounces (avdp) | 28.35 | grams | g | g | grams | 0.0353 | Ounces (avdp) | oz |
| lb | Pounds (avdp) | 0.454 | kilograms | kg | kg | kilograms | 2.205 | Pounds (avdp) | lb |
| T | Short tons (2000 lb) | 0.907 | megagrams | mg | mg | megagrams (1000 kg) | 1.103 | short tons | T |
| | | VOLUME | | | | | VOLUME | | |
| fl oz | fluid ounces (US) | 29.57 | milliliters | mL | mL | milliliters | 0.034 | fluid ounces (US) | fl oz |
| gal | Gallons (liq) | 3.785 | liters | liters | liters | liters | 0.264 | Gallons (liq) | gal |
| $ft^3$ | cubic feet | 0.0283 | meters cubed | $m^3$ | $m^3$ | meters cubed | 35.315 | cubic feet | $ft^3$ |
| $yd^3$ | cubic yards | 0.765 | meters cubed | $m^3$ | $m^3$ | meters cubed | 1.308 | cubic yards | $yd^3$ |
| Note: Volumes greater than 1000 L shall be shown in $m^3$ | | | | | | | | | |
| | | TEMPERATURE (exact) | | | | | TEMPERATURE (exact) | | |
| ºF | Fahrenheit temperature | 5/9 (ºF-32) | Celsius temperature | ºC | ºC | Celsius temperature | 9/5 ºC+32 | Fahrenheit temperature | ºF |
| | | ILLUMINATION | | | | | ILLUMINATION | | |
| fc | Foot-candles | 10.76 | lux | lx | lx | lux | 0.0929 | foot-candles | fc |
| fl | foot-lamberts | 3.426 | candela/$m^2$ | $cd/cm^2$ | $cd/cm^2$ | candela/$m^2$ | 0.2919 | foot-lamberts | fl |
| | | FORCE and PRESSURE or STRESS | | | | | FORCE and PRESSURE or STRESS | | |
| lbf | pound-force | 4.45 | newtons | N | N | newtons | 0.225 | pound-force | lbf |
| psi | pound-force per square inch | 6.89 | kilopascals | kPa | kPa | kilopascals | 0.145 | pound-force per square inch | psi |

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# Technical Advisory Committee

Each research project is overseen by a technical advisory committee (TAC), which is led by an ITD project sponsor and project manager. The Technical Advisory Committee (TAC) is responsible for monitoring project progress, reviewing deliverables, ensuring that study objective are met, and facilitating implementation of research recommendations, as appropriate. ITD's Research Program Manager appreciates the work of the following TAC members in guiding this research study.

**Project Sponsor – John P. Bilderback, P.E.**

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**Dana Dietz**
**Jeff Drager,**
**Clint Hoops,**
**Keith Nottingham**

**FHWA-Idaho Advisor – Kyle Holman, PE**

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# Executive Summary/Abstract

The newly developed 56-day Miniature Concrete Prism Test (MCPT) was successfully implemented for the first time in Idaho through this research project. Fourteen (14) different aggregate materials (both coarse and fine fractions), including a non-reactive reference aggregate, were collected from various sources across and adjacent to Idaho, and were tested using the 56-day MCPT as well as the commonly used Accelerated Mortar Bar Test (AMBT; ASTM C1260). Additionally, the 1-year Concrete Prism Test (CPT; ASTM C1293) was carried out on selected aggregates. Finally, a shortened version of the ASTM C1293 test was also explored to assess its suitability for application. Other than the reference aggregate material, all aggregate materials tested were designated as being ASR-susceptible with different reactivity levels. The rate of expansion of the MCPT concrete bar was proportional to the duration or age of the test. Most of the fine aggregate fractions tested using the MCPT method were identified as being "very highly reactive". On the other hand, reactivity levels of the coarse aggregate fractions varied between "moderately reactive" to "very highly reactive". Several of the aggregate materials were tested at two laboratories (Boise State University and University of Idaho) to get a measure of possible inter-laboratory variations. Comparing the results from the two laboratories indicated acceptable levels of within-laboratory as well as multi-laboratory variations.

The MCPT results were consistent with those from the 14-day AMBT and 1-year CPT methods to characterize the aggregate materials as being ASR-susceptible or not. However, the test results did not clearly demonstrate better correlation with one of the commonly used test methods over another. No assessments could be made regarding possible instances of false-positive or false-negative results, because all the aggregate materials tested in the current study were found to be ASR-susceptible under all test methods. The researchers conclude that to get a better assessment of the suitability of the MCPT method for implementation into practice, the Idaho Transportation Department (ITD) needs to initiate further studies that will compare the laboratory test results with field performance of selected aggregate types. In addition, these subsequent studies should take special care to identify aggregate types falling under both "reactive" as well as "non-reactive" categories in terms of ASR susceptibility. Besides comparing the laboratory test results with field performance, these subsequent studies should also focus on evaluating different ASR-mitigation approaches using this method. Although the MCPT results from this study were consistent with the AMBT and CPT results, it could not be definitively concluded whether or not implementation of this method will mark a significant improvement to ITD's current practices. Although significant time savings can be realized compared to the 1-year long CPT method, advantages over the 14-day AMBT could not be clearly identified. It is recommended that ITD continues testing all aggregate materials being used in concrete applications using the MCPT method. This will facilitate long-term comparison of the laboratory test results with field performance. Implementation of this method into practice as the sole method of evaluating ASR susceptibility can be justified only after completion of subsequent studies focusing on field performance and testing of reactive as well as non-reactive aggregate materials. Once proved to be a reliable method, the MCPT can be used instead of the 1-year CPT to test the effectiveness of ASR mitigation approaches utilizing Secondary Cementitious Materials (SCMs).

# Chapter 1
# Introduction

## Background

Alkali-aggregate reaction (AAR) is a reaction in concrete between the alkali hydroxides and certain types of aggregates. The alkali hydroxides mainly come from the Portland cement. Portland Cement Concrete (PCC) is the most widely used construction material [1]. Usually, concrete consists of 60% to 75% aggregates, 10% to 15% of binding agents (cement and other cementitious materials), and water. The chemical reactions between aggregates and binding agents are complicated. In concrete, most aggregates are more or less chemically inert. Therefore, not all aggregate sources exhibit AAR. However, some natural aggregates contain specific quantities of amorphous silica and carbonate, which both react with the alkalis (sodium, Na, and potassium, K) from cementitious materials. This interaction is widely known as AAR. AAR in concrete can be a major concern as far as durability and performance of bridges, pavements, and other transportation infrastructures is concerned. AAR often leads to definite reductions in a structure's serviceability and lifespan [2,3]. Based on the mineral types involved in the reaction, AAR can be sub-divided into two categories: Alkali-Silica Reaction (ASR), and Alkali-Carbonate Reaction (ACR). The primary difference between these two reaction types is based on whether the alkaline component reacts with the siliceous or carbonate phases in the aggregates.

ASR is the most common form of AAR observed in civil engineering infrastructure [4]. It is a destructive chemical reaction involving the active silica constituents (reactive minerals) of aggregates, and alkalis in the cement and other pozzolanic materials. This reaction causes a definite expansion in the presence of moisture or a pore solution of concrete [5]. In 1923, many concrete structures in the USA were observed to have developed severe cracking with an unidentified cause. Stanton [4] recognized for the first time that alkalis (Na and K) in the paste combined with silica from the aggregate, in a deleterious reaction dubbed 'alkali-silica reaction' [6]. ASR forms a swelling gel that can expand and cause internal stresses in cementitious materials leading to cracking, loss of strength, and, eventually, concrete failure. ASR is of more concern and is far more widespread than ACR as aggregates containing reactive silica are more common compared to those with reactive carbonates. Three essential conditions are necessary to create ASR-induced damage in concrete structures [7]:

1. Presence of reactive siliceous components in aggregates (both coarse and fine) at an optimum level and high-alkali cement;
2. Sufficient availability of $OH^-$ ions and alkalis ($Na^+$ and/or $K^+$). A highly alkaline concrete pore solution ($pH > 13.2$) ensures enough supply of alkali hydroxides;
3. Sufficient moisture (above 75% RH) and climate.

Some of the other factors include exposure, any mitigating measures adopted (i.e., additives, sealers, etc.), and time.

## Problem Statement

Several test methods have been developed to identify ASR in concrete. Among the developed test methods, one popular test method is the one specified in ASTM C1293 [8]. This test method has been found to have a strong correlation with field performance in terms of ASR susceptibility of aggregates used in concrete. However, the ASTM C1293 test takes one full year to complete for aggregate evaluation. In instances where different mitigation methods are to be tried, the test can take as long as two years. As an alternative evaluation approach, the test method described in ASTM C1260 [9] takes only 14 days to complete. This test method is the same as the one detailed in AASHTO T 303 [10]. Although this test is significantly faster than the one described in ASTM C1293, it is known to subject the aggregates being tested to a significantly harsh environment; therefore, leading to false positive results in several cases. In other words, aggregates that exhibit good field performance having none or very little ASR potential may be incorrectly identified by this test method as being reactive.

The Idaho Transportation Department (ITD) currently uses the AASHTO T 303 [10] or ASTM C1260 [9] approach for assessing the ASR susceptibility of aggregates used in concrete. Historically these tests have led to conflicting results depending on the length and type of the test even on the same aggregate source. A brief description of ASTM C1260-AMBT and ASTM C1293-CPT test methods will be given in Chapter 2 of this report. In summary, the currently used test methods are either too harsh (ASTM C1260) or too long (ASTM C1293); the actual life of concrete prepared with these aggregates is therefore not known. Accordingly, there is a need for a well-validated method that can be used to evaluate the susceptibility of aggregates to ASR in Idaho within a reasonable time period.

Recently, a new test procedure, AASHTO TP 110 [11], was developed to overcome the shortcomings of the ASTM C1260. This test method is also known as the Miniature Concrete Prism Test (MCPT), and was developed as an approach that would achieve the much desired balance between expediency and accuracy when it comes to assessing the ASR susceptibility of concrete aggregates. The AASHTO TP 110 test takes 56 days to complete, with an additional 28 days needed in the case of slow-reacting aggregates. This method has been found to provide good correlations with ASTM C1293 results, as well as field performance.

The current research study was undertaken to assess the ASR susceptibility of different aggregates from across the state of Idaho using the newly developed AASHTO TP 110 test method. Note that since the start of the current research study, the AASHTO TP 110 test method was officially adopted by AASHTO and designated as AASHTO T 380. However, the current research study did not compare the detailed procedure for AASHTO TP 110 with that of AASHTO T 380. Therefore, all results and discussions presented in the current report correspond to the AASHTO TP 110 test procedure before its official adoption by AASHTO as T 380.

## Objectives

The primary objective of the current research study was to evaluate advantages (as compared to other test methods) associated with implementing AASHTO TP-110 within ITD specifications to characterize the ASR potential of Idaho aggregates. First, the baseline ASR susceptibility of several selected Idaho aggregates was established. ASR potentials of these aggregates were then quantified using the AASHTO TP 110 test protocol, and the results were compared against those from ASTM C1260 and ASTM C1293. The primary goal was to assess whether or not the implementation of the MCPT described in AASHTO TP 110 into ITD practice will facilitate better identification of ASR susceptibility of Idaho aggregates. More importantly, if found to be accurate, this method can be used to optimize the mix design (e.g., replacing a portion of cement with supplementary cementitious materials such as fly ash and slag, adjusting w /c ratio, etc.) to produce a mix that has better resistance to ASR. With ITD's ongoing efforts to implement performance-based specifications, such alternatives to modify existing mix designs can be quite significant.

## Report Organization

The contents of this report have been divided into five chapters.

Chapter 2 presents an extensive review of published literature on the mechanism of ASR, factors that affect ASR in concrete structures, and different available methods to assess the ASR potential of various aggregates. Chapter 2 also presents details about the recent development of the AASHTO TP 110 test protocol, its current state of practice in the United States, and results from different research efforts targeted at validating the MCPT results, and correlating them with those from other test methods.

Chapter 3 presents details about the development of the laboratory test matrix for the current project. The procedure adopted for material selection has been discussed, and details of the laboratory test procedures have been presented.

Chapter 4 presents results from the extensive laboratory test program. Detailed discussions of the results from ASTM C1260 (14-day AMBT method), ASTM C1293 (1-Year CPT method) and AASHTO TP 110 (56-day MCPT method) have been presented. Additionally, results from a new 6-month test, named the Accelerated Concrete Prism Test (ACPT) have also been presented in this chapter. The test results have been analyzed to draw inferences regarding the adequacy of the AASHTO TP 110 test protocol for assessing the ASR potential of Idaho aggregates.

Chapter 5 summarizes major findings from the research study and presents recommendations for future research.

# Chapter 2
# Literature Review

## Alkali-Silica Reaction

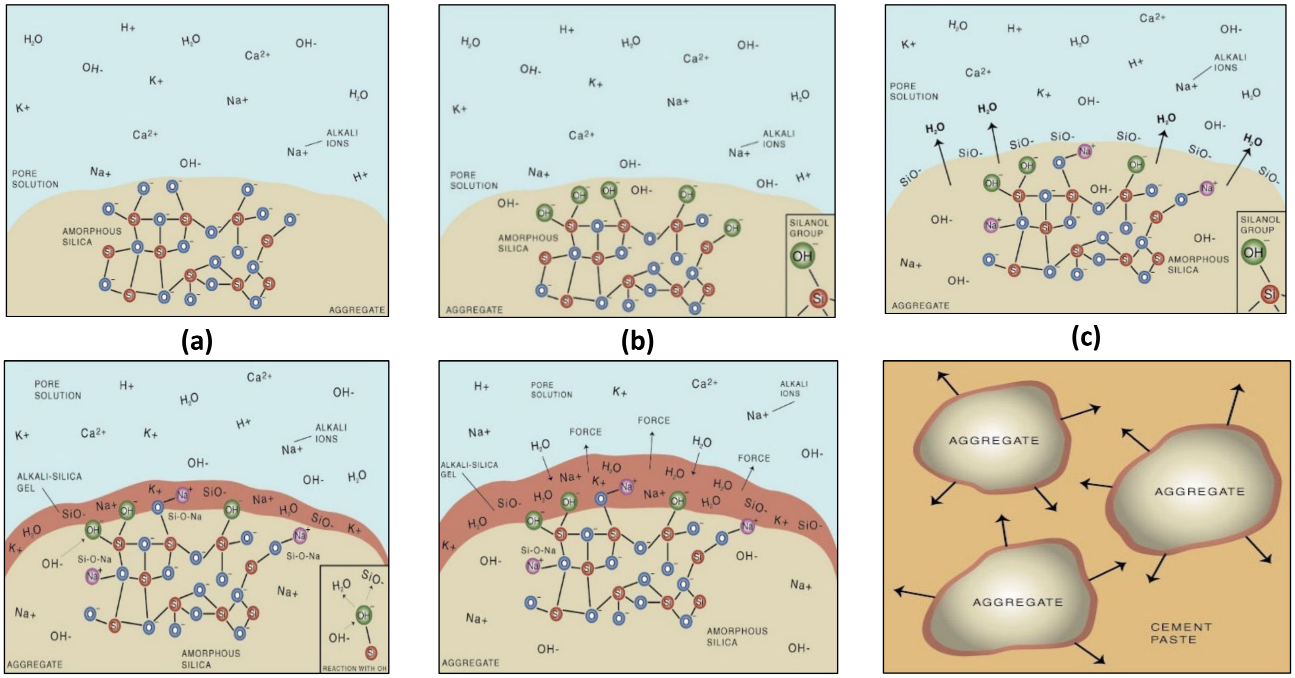
Alkali-Silica Reaction (ASR) has been recognized for over a century as a major distress in concrete. It is considered the second main concern, after concrete corrosion, facing highway concrete structures (i.e., bridges and pavements) in the field [4]. In the United States, ASR is a major cause of the deterioration of highway concrete structures (i.e., bridges and pavements) [12]. ASR is a chemical reaction between silica in aggregates and alkalis in cement in the presence of moisture. This reactivity causes undue expansion and cracks in hardened concrete, which over time, can result in complete destruction of concrete structural integrity. Deformation due to ASR is a phenomenon that was first recognized during the 1940s in America, and since then has been observed in many other countries [4].

According to Diamond [13], the deterioration of concrete caused by ASR is continual, expensive, and generally slow. The ASR reaction produces an alkali-silica gel over time, which leads to progressive distortion of concrete internal forces triggering a loss in serviceability and longevity [4,13]. The ASR-induced distress, in turn, leads to significant damage in concrete structures and eventually causes structural collapse [14-17]. This chapter provides an overview of the ASR mechanism, its effect on concrete structures, test procedures used to assess aggregate susceptibility to ASR, as well as commonly used mitigation procedures to address the problem of ASR in concrete. Despite numerous research efforts over several decades dedicated to studying the ASR phenomenon, its mechanism is still not completely understood due to the complex nature of chemical reactions involved. Nevertheless, alkalis contained in the pore solution, reactive amorphous silica present in aggregates, and the presence of water have been unanimously identified as the three primary factors affecting ASR.

## Mechanism and Chemistry of ASR

Several steps are associated from the beginning of the ASR process to the formation of ASR gel, which eventually causes the concrete structures to crack. Usually, cement is responsible for sharing the alkali during the ASR process as it contains alkalis in the range of 0.2 to 1.5 percent of $Na_2O$ (Sodium Oxide). Even in situations where the cement has a low alkali content, ASR can take place due to the presence of alkaline admixtures, aggregates that are contaminated, penetration of seawater, and deicing solutions. Previous studies (e.g., Farny and Kerkhoff [5], Diamond [18], Latifee [19], and Thomas et al. [20]) have presented excellent summaries of the chemical reaction involved in ASR. Some of the most significant aspects related to ASR have been summarized in the following sections with appropriate references to the respective sources.

Figure 1 [19] schematically illustrates the most significant steps that constitute the ASR phenomenon. At first, the siliceous aggregate gets in contact with the concrete pore solution (see Figure 1a).



(a) (b) (c)

(d) (e) (f)

**Figure 1. (a) Siliceous Aggregate in Pore Solution; (b) Surface of Aggregate Attacked by OH⁻; (c) Silanol Groups (Si-OH) on Surface are Broken Down by OH⁻ into SiO⁻ Molecules; (d) Formation of Alkali-Silica Gel; (e) Expansion of Alkali-Silica Gel; (f) Expansionary Pressure Exceeds the Tensile Strength of the Concrete Resulting in Cracks [19]**

Next, the Alkali-silica reaction begins when the aggregate surface (siloxane group) is attacked by hydroxyl ($OH^-$) ions. This phenomenon is illustrated in Figure 1b, and the corresponding equation has been presented in Figure 2.

$$\mathbf{H_2O + Si - O - Si \rightarrow Si - OH \ldots OH - Si}$$

**Figure 2. Equation of Alkali attacking the aggregate's siloxane group**

In presence of a high concentration of hydroxyl ($OH^-$) ions, silica tends towards dissolution first by neutralization of the silanol groups (Si-OH) and then by an attack on the siloxane groups (Si-O-Si) as illustrated in Figure 1c. The reactions may be represented using the following equations (see Figure 3).

$$\mathbf{Si - OH + OH^- \rightarrow SiO^- + H_2O}$$
$$\mathbf{Si - O - Si + 2OH^- \rightarrow 2SiO^- + H_2O}$$

**Figure 3. Equations for dissolution and neutralization of aggregate's silanol group**

As shown in Figure 1d, released negatively charged $SiO^-$ ions attract positively charged alkali cations such as sodium ($Na^+$) and potassium ($K^+$), which are abundant in the concrete pore solution, forming an alkali-silicate gel ($CaO$-$Na2O$/$K_2O$-$SiO_2$-$H_2O$) around the aggregate [21,22]. The "Alkali-silicate" gel is also known as the "alkali-silica" gel. The gel is primarily composed of sodium, potassium, and silica, with small amounts of calcium. Figure 4 shows the chemical equations involved in this step.

$$\mathbf{Si - OH + Na^+ + OH^- \rightarrow Si - O - Na + H_2O}$$
$$\mathbf{Si - O - Si + 2OH^- + 2Na^+ \rightarrow 2(Si - O - Na) + H_2O}$$

**Figure 4. Equations for the formation of Alkali-silicate gel**

The Alkali-silica gel formation occurs in the presence of water, expanding and exerting osmotic pressure against the surrounding paste or aggregate (see Figure 1e). When this expansion pressure exceeds the tensile strength of the concrete, the concrete cracks (see Figure 1f). Other symptoms of ASR damage include: the presence of gel, and staining. Continued expansion of the gel leads to further cracking of the concrete. With time, this continued cracking increases the permeability of the concrete, which allows more water to get inside the concrete. Therefore, the ASR phenomenon continues as a vicious cycle [18,23].

## Factors Affecting Alkali-Silica Reactions (ASR)

It should be noted that the swelling gel of ASR does not directly cause concrete distress, but as the swelling gel absorbs moisture, it expands, and subjects the surrounding concrete to tensile stresses. When these tensile stresses exceed the tensile strength of concrete, progressive cracking and associated deterioration occurs. As already mentioned in the previous chapter, the three main components widely accepted as important for ASR to occur in concrete are:

1. Presence of reactive siliceous components in aggregates (both coarse and fine);
2. Adequate alkali content from cementitious materials; and
3. Presence of moisture along with other factors (e.g., temperature, relative humidity, additives).

### *Reactive Aggregate*

The quality of the aggregate used in the concrete has a major influence on the durability and chemical stability of the concrete and road surface. Aggregates constitute 60% to 75% of the concrete volume (and more by mass), which means the concrete aggregates (coarse and fine) have a huge influence on the concrete properties. Similarly, aggregates play a major role in governing the properties of concrete that is susceptible to ASR. The American Association of State Highway and Transportation Officials (AASHTO) and the American Society for Testing and Materials (ASTM) have developed standards to provide engineering guidelines governing the quality of cement, aggregates, as well as concrete construction. Silica ($SiO_2$) is a component of many aggregates. Not all forms of silica react significantly with the pore solution of concrete and, thus, not all siliceous aggregates produce damaging ASR gel. ASR is a function of the form/degree of crystallinity, grain size, texture, and proportion of the reactive silica within the reactive aggregate [4]. The reactivity of siliceous aggregates depends largely on how disordered the structure of the silica phase is. For example, both Opal and Quartz have silica minerals with a similar chemical composition (primarily composed of SiO). However, as a mineral, quartz is stable, but opal is highly reactive in its mineral form. Figure 5 shows schematics of the structural arrangement of quartz and opal minerals. Due to its regular structural arrangement, quartz will not react deleteriously regardless of the alkali content within concrete. On the other hand, Opal has a highly disordered (amorphous) structure that renders it unstable at high pH. Accordingly, aggregates containing significant quantities of the mineral opal may be expected to react and result in expansion when used in concrete, provided there is sufficient alkali present [24].

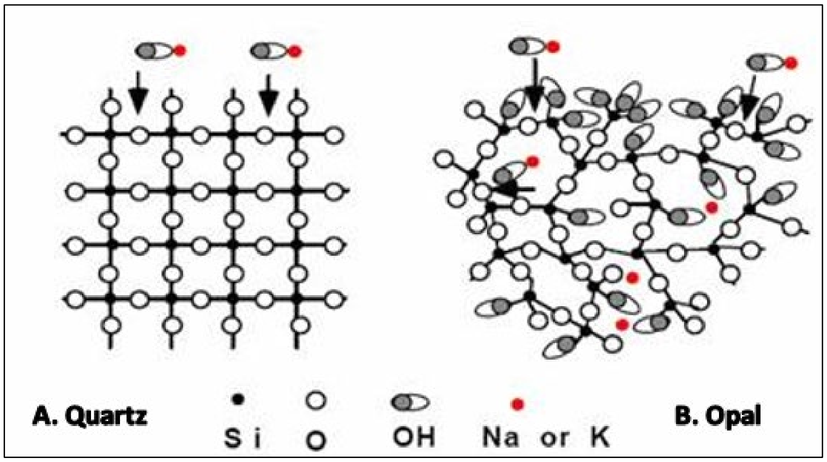


**Figure 5. Solubility and Structure of Quartz and Opal (Bleszynski and Thomas, 1998)**

The basic structure of silicates (in aggregates) involves a framework of a silicon-oxygen tetrahedron. Each oxygen atom is shared between two silicon atoms, in which each silicon atom is bonded to four oxygen atoms (called the Siloxane Bridge). A regular arrangement of the basic Si-O tetrahedron creates a crystalline structure (quartz), whereas an irregular arrangement of the tetrahedron creates structures that range from poorly crystalline (chalcedony) to amorphous in nature. The degrees of reactivity of these reactive forms of silica are designated in their decreasing order as follows: opal, tridymite, cristobalite, volcanic glass, cryptocrystalline (present in igneous rock), microcrystalline, quartz, chert, Chalcedony, strained quartz (present in metamorphous rock), and Volcanic glass [13,25]. These minerals may be found in the following rock types: shale, sandstone, silicified carbonate rocks, chert, flint, quartzite, quartz-arenite, gneiss, argillite, granite, greywacke, siltstone, arenite, arkose, and hornfels. Although petrographic studies play an important role in understanding and determining the presence of reactive minerals, appropriate performance testing of specific aggregate sources is recommended to assess ASR susceptibility. The degree of crystallinity and number of defects present in the lattice affect the potential alkali reactivity and solubility of siliceous aggregates [15]. However, it should be noted that the form of silica present in an aggregate is not the only factor that governs its reactivity with alkaline components. Other important factors that govern aggregate reactivity include:

### *Aggregate Size*

Aggregate size plays an important role in determining aggregate reactivity. Stanton [4] showed the expansion increases as the particle size decreases (surface area increases).

### *Amount (Quantity) and Nature of the Distribution of Reactive Constituents inside Aggregates*

The aggregate reactivity is largely governed by:

a) Whether the reactive constituents are distributed within the aggregate in a homogeneous or inhomogeneous manner;
b) Whether the whole aggregate particle is reactive (acid volcanic rock) or certain reactive constituent(s) inside an aggregate is(are) reactive.
c) If the aggregate comprises components such that the fine cementing material is reactive, but the coarse grains are nonreactive.

### *Role of aggregate porosity*

Pore connectivity and other internal structures have a significant effect on the ingress of $OH^-$, $Na^+$, and $K^+$ ions into the aggregates. High porosity/pore connectivity can enhance the ingress of ionic species and increase the chance for ASR to occur with a much faster rate, provided enough reactive constituents are present [26,27].

### *Reactive Aggregate in Idaho*

In Idaho, several aggregate sources have been reported to be reactive as far as ASR susceptibility is concerned. Idaho Engineering and Geology, Inc. (IEG) examined and evaluated aggregates from numerous sources in Idaho, and observed that several of them exhibited high ASR susceptibility. Over the years, resarchers and practitioners have developed several standard tests, specifications, and mitigation procedures to assess the ASR susceptibility of aggregates before they are used in concrete applications. Some of the commonly used tests include those specified in: ASTM C295, ASTM C1260, and ASTM C1293. In addition, different mitigation protocols to limit ASR in concrete have been extensively documented in the literature [12].

In a recent research study titled, “Lithologic characterization of active ITD aggregate sources and implications for aggregate quality”, Gillerman and Weppner [28] collected aggregate samples from 40 concrete-certified material sources across the state of Idaho, and provided their lithological characteristics as well information about their ASR susceptibility experimentally. Figure 6 presents a map of aggregate sources across Idaho produced as a deliverable of the above-mentioned research study. This map also includes information about the AASHTO T 303 (AMBT) and ASTM C1293 (CPT) test results for the aggregates corresponding to each of the sources. AASHTO T 303 and ASTM C1293 results were used as proxies while evaluating the general ASR potential of a particular aggregate source. Table 1 lists the aggregate sources tested by Gillerman and Weppner [28] along with the source lithological properties as well as the AASHTO T 303 and ASTM C1293 results.

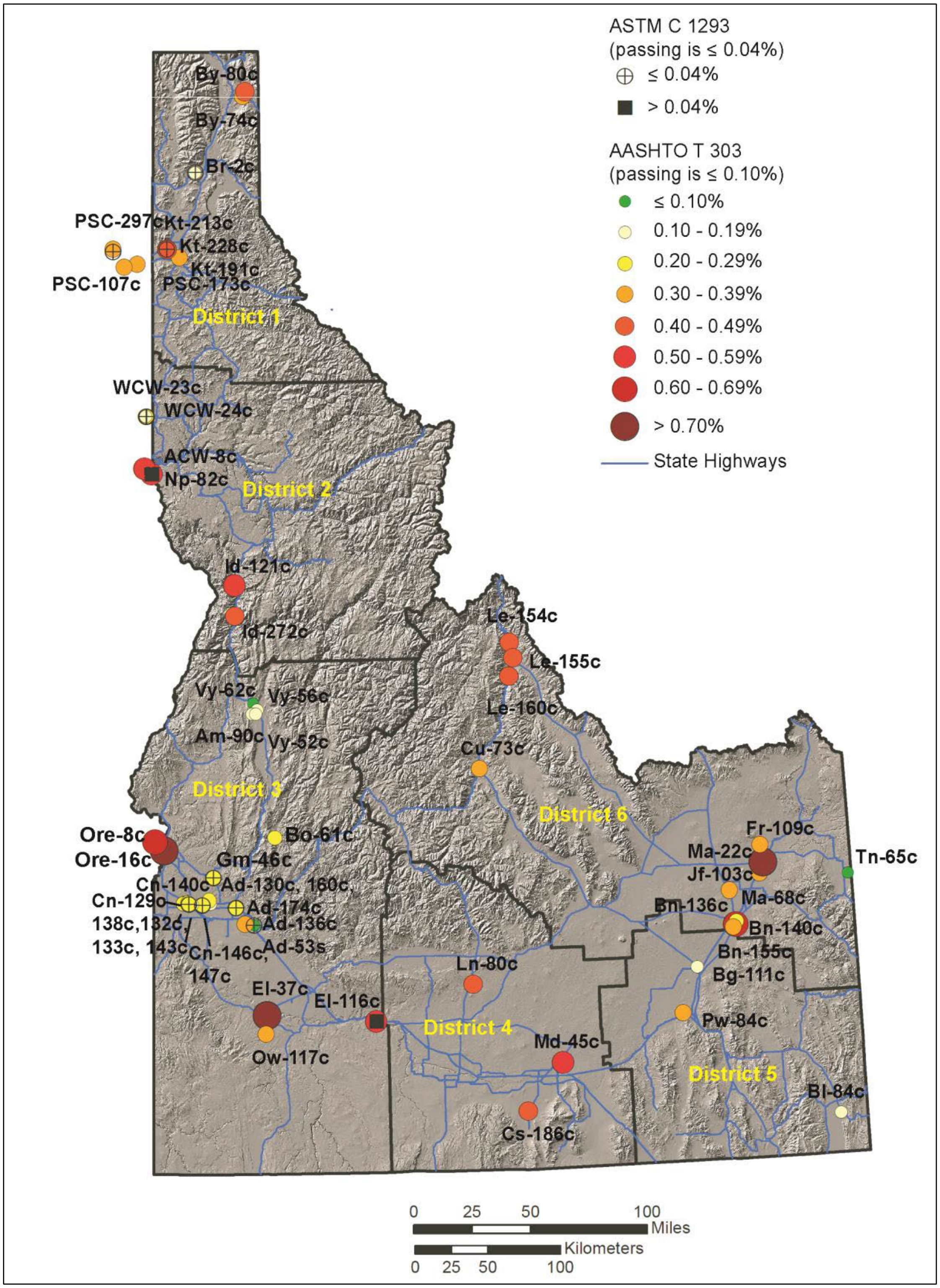


Figure 6. Map of Aggregate Sources, AASHTO T 303, and ASTM C 1293 Results [28]

**Table 1. Summary of RP 212 Selected Aggregates Source, Lithological Inventory and Test Results [28]**

| ITD District | Country | Sample Type | General Lithologic Inventory of Source | AASHTO T 303 (≤ 0.1 % is passing) | (ASTM C 1293) |
|---|---|---|---|---|---|
| D1 | Boundary | BY-74c | 60% quartzite, 25% argillite/siltite, 10% granodiorite | 0.30-0.39% | NA |
| | Kootenai | Kt-213c | 45% quartzite, 30% argillite/siltite, 10% calcareous siltstone/siltite, 10% granodiorite | 0.40-0.49% | ≤ 0.04% |
| | | PSC-173c | 40% quartzite, 30% argillite/siltite, 10% calcareous siltstone/siltite, 10% granodiorite | 0.30-0.39% | NA |
| D2 | Idaho | ID-121c | 55% quartzite, 20% basalt, 10% andesite, 5% rhyolite, 3% opal | 0.40-0.49% | NA |
| | Nez Perce | NP-82c | 35% basalt, 25% rhyolite, 20% quartzite, 15% andesite | 0.50-0.59% | > 0.04% |
| D3 | Canyon | CN-140c | 30% granodiorite, 20% rhyolite/dacite, 10% andesite, 5% basalt, 5% quartzite | 0.20-0.29% | ≤ 0.04% |
| | Elmore | El-116c | 25% basalt, 20% quartzite, 20% opal, 15% rhyolite, 10% andesite, 10% siliceous argillite | 0.50-0.59% | > 0.04% |
| | | ORE-8c | 30% basalt, 20% rhyolite, 15% granodiorite, 10% quartzite, 5% chalcedony | 0.50-0.59% | NA |
| D4 | Lincoln | LN-80c | 20% rhyolite, 20% andesite, 20% siltstone, 15% quartzite, 10% siliceous argillite | 0.40-0.49% | NA |
| | Minidoka | Md-45c | 25% quartzite, 20% basalt, 20% rhyolite, 15% siltstone, 15% obsidian | 0.50-0.59% | NA |
| D5 | Bingham | Bg-111c | 45% quartzite, 10% quartzite, 5% sandstone,5% basalt, 5% rhyolite, 5% obsidian, 1% opal | 0.10-0.19% | NA |
| | Power | Pw-84c | 70% quartzite, 10% sandstone, 10% basalt, 5% rhyolite | 0.30-0.39% | NA |
| D6 | Blaine | Bn-155c | 40% quartzite, 20% obsidian, 10% rhyolite, 10% basalt, 5% opal | 0.60-0.69% | NA |
| | Lemhi | Le-154c | 45% quartzite, 20% rhyolite, 10% andesite, 10% sandstone | 0.40-0.49% | NA |
| | Madison | Ma-22c | 30% basalt, 25% rhyolite, 15% andesite, 10% granite, 10% quartzite | >0.70% | NA |

### *Alkalinity of Cementitious materials*

Portland cement is the primary source of alkalis responsible for ASR in concrete. Silica fume, Natural Pozzolans, Slags and fly ash (supplementary cementing materials in concrete); external source (such as seawater and deicing salts) and admixtures also contribute to the total alkali content in concrete, and therefore, can lead to ASR [18,29]. Although cement and other cementitious materials contain numerous alkaline metals, the presence of Sodium, $NA^+$, and potassium, $K^+$ ions primarily govern ASR in concrete.

The conventional North American Portland cement contains 0.2% to 1.2% $Na_2O_{eq}$ , whereas alkali contents as high as 1.65% of $Na_2O$ or more are found worldwide [18]. Despite the low percentage of alkalis compare to other Portland cement oxide, the high solubility of these alkalis makes them dominate the concrete pore (filled with a solution containing $OH^-$ and alkali ions, i.e., $Na^+$ and $K^+$, playing an essential role in developing concrete ASR induced damage. The total alkali content formed in a concrete mixture increases as a result of external sources such as seawater, water from the industries using sodium and potassium solution, the groundwater, etc., and admixtures such as retarders; plasticizers, water reducers, and air-entraining admixtures, etc., which may contain $Na^+$ and $K^+$ ions. All these factors, in combination or individually, lead to high ASR in concrete.

### *Role of Environmental Factors*

Different environmental factors can increase the ASR-susceptibility of concrete. Two main environmental factors affecting concrete ASR are:

1. Moisture content, temperature, and associated concrete alkali redistribution due to seasonal climatic variations (temperature and wetting/drying cycles); and
2. Penetration of alkalis from external sources such as seawater and deicers.

It is important to note that an optimum combination of silica from aggregates source and alkalis from cement is essential to initiate ASR. However, the environmental factors mentioned here are essential to make ASR expansive (deleterious). Water is required to initiate the alkali-silica reaction in concrete, in which it acts as a transporter of the alkali ions from the Portland cement. The pressure causing concrete cracks originates when the gel absorbs water leading to greater expansion and cracking in the surrounding paste over a long period. Therefore, high ASR expansion in concrete mixture is developed generally by highly reactive aggregates with high-alkali cement content when exposed to a substantial amount of moisture; highly reactive aggregates and high-alkali cement content without the presence of sufficient moisture show no or little expansion. [30]

In addition, an increase in Relative Humidity (RH) of concrete has been found to increase the severity of ASR. Pedneault [31] reported that the chemical reactions involved in ASR would cease if the internal RH of the concrete falls below 80%. Therefore, it is quite possible to see different ASR severities in different portions of the same structure if one side of the structure is constantly exposed to greater moisture contents compared to other sides. Lastly, the rate of expansion of the alkali-silica gel also increases as temperature increases [30].

## Evaluation of Alkali-Silica Reaction (ASR)

Over the years, researchers and practitioners around the world have developed and proposed different test methods to evaluate the ASR susceptibility of aggregates and concrete. Among the different test methods developed, the following three methods are commonly used in the United States:

1. ASTM C295: Standard Guide for Petrographic Examination of Aggregates for Concrete

2. ASTM C1260: Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)
3. ASTM C1293: Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction

Note that ASTM C1260 is very similar to AASHTO T 303 *"Standard Method of Test for Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali–Silica Reaction"*. Besides the above-listed test methods, a recently developed test method at Clemson University [7] was first designated as AASHTO TP 110. This test method has since been officially adopted by AASHTO as T 380 "Standard Method of Test for Potential Alkali Reactivity of Aggregates and Effectiveness of ASR Mitigation Measures (Miniature Concrete Prism Test, MCPT)".

The following paragraphs present brief overviews of these test methods highlighting their salient features.

### *ASTM C 295: Aggregate Petrographic Examination*

This method was first developed in 1954 by Mather and Mather [32], and was later modified in 2008, and subsequently adopted as a standard test method (ASTM C295). This test method represents reliable and fast way to identify reactive aggregates susceptible to Alkali-Silica Reaction. Visual and Macroscopic examination are performed on prepared potential aggregate samples. When necessary, the petrographic examination can be accomplished by using advanced methods such as X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), or Infra-Red (IR) Spectroscopy.

### *ASTM C 1260: Accelerated Mortar Bar Test (AMBT) Method*

The Accelerated Mortar Bar Test (AMBT) method adopted by ASTM C1260 was originally developed at the National Building Research Institute (NBRI) in the Republic of South Africa by Oberholster and Davies[33], and was later adopted by ASTM. This test method is a variant of ASTM C227 "*Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)",* which was withdrawn from ASTM specifications in 2018. In the AMBT test method, 50 mm x 50 mm x 285 mm (1-in. x 1-in. x 11.25-in.) mortar bars are prepared using a standard aggregate gradation of ASTM C33 specification, and the Portland cements meeting the requirements of ASTM C150.

This test procedure involves complete immersion of the mortar bars in NaOH solution at 80° C (176° F) for 14 days. This test produces results within 16 days from the time of casting, and is used to evaluate the coarse and fine aggregates reactivity levels separately. Mortar bar expansions of less than 0.10% at 16 days after casting are mostly indicative of non-reactive aggregates. If the average expansion is between 0.11% and 0.30%, the tested aggregates are designated as being *'slow or moderately reactive'*. If the average expansion exceeds 0.30%, the aggregate is designated as being '*deleteriously reactive'*.

Although this test method facilitates relatively *'quick'* assessment of aggregate ASR susceptibility, it has been known to produce false positive and false negative results in several instances [8]. In other words, aggregates that do not exhibit ASR susceptibility in the field may be designated by this test as being reactive (false positive); similarly, aggregates that do exhibit ASR susceptibility in field applications, may be designated by this test as being non-reactive (false negative). Folliard et al.[34] reported that five of their tested aggregates passed the ASTM C1260 test, but failed the 'more reliable' concrete prism test (ASTM C1293), presenting an example where False Negative results were obtained through ASTM C 1260 testing. On the other hand, Gillerman and Weppner[28] recently reported false-positive cases where several Idaho aggregates (e.g. Gm-46c, Ad-130c and Ad-174c) failed during AMBT (AASHTO T 303), but were found to be non-reactive upon performance of the 1-year long ASTM C1293 test. Although widely accepted into practice, this test has been identified by researchers [29, 34-36] to have the following limitations:

1. Harsh testing conditions can often lead to false positive results;
2. This test requires the coarse aggregates to be crushed, washed, and graded to a sand size less than 4.75 mm. Excessive crushing may alter the availability of reactive silica within the aggregate matrix; this may lead to different aggregate reactivity during testing;
3. This test process involves a storage temperature of 80° C (176° F); this temperature is too high compared to typical field exposure temperatures, and therefore, may cause unrealistic levels of ASR gel expansion in the test specimens;
4. The mix proportions to be used during this test is fixed, and therefore, this test method cannot be employed to evaluate a concrete mixture with a specific combination of cement, admixtures, and aggregates;
5. Excessive number of false positive and false negative results from this test brings the reliability associated with this test into question.

### *ASTM C1293: Concrete Prism Test (CPT) Method*

This method was developed to overcome limitations associated with other test methods used to assess the ASR susceptibility of aggregates; the primary idea was to measure the ASR susceptibility using a concrete specimen rather than carrying out tests on only aggregates or mortar bars. The test method involves measuring the change in length of concrete prisms made with both coarse and fine aggregates. A non-reactive fine aggregate is used to make the concrete specimen when testing the ASR susceptibility of coarse aggregates, and vice versa.

Swenson and Gillott[37] developed the ASTM C1293 test method to identify alkali-silica reactive rocks found in southern Ontario, Canada. The concrete prisms, 75 mm x 75 mm x 285 mm (3 in. x 3 in. x 11.25 in.), are stored over water in sealed containers at 100°F (38°C). Aggregates are considered acceptable as far as ASR susceptibility is concerned, if the average expansion of the concrete prisms is less than 0.04% after 1 year. For mitigation, material combinations are considered acceptable if the average expansion of concrete prisms is less than 0.04% at two (2) years.

Although this test has been found to give reliable results that correlate well with the actual performance of concrete in the field, two major limitations have been identified:

- <u>*Long Duration:*</u> This test requires at least one or two years to complete, depending on the test purpose, and is therefore, impractical for screening aggregates for a specific project, or evaluating ASR mitigation measures. This limitation is particularly significant for projects with expedited construction schedules.

- *Alkali Leaching:* During the test, the alkalis in concrete prisms can potentially leach out of the prisms due to convective air currents that develop within the storage container. As a result, the CPT prism specimens can exhibit less expansion than their corresponding concrete blocks stored outside with the same level of alkalis. Indeed, past research has found that as much as 20% of the alkalis originally in the concrete prism leach out into the water reservoir after just 90 days, and approximately 35% leach out after 1 year [38].

### *Accelerated Concrete Prism Test (ACPT)*

As a result of the first limitation (long testing duration) found in ASTM C1293 (CPT) (Ideker et al. [39]), Ranc and Debray [40] proposed accelerating the rate of expansion in the concrete prism test by proposing a test known as the "Accelerated Concrete Prism Test (ACPT)"; the primary focus was to shorten the test duration by increasing the exposure temperature to 60°C (140°F). In this test, the testing time was reduced from one year to six months by subjecting the test samples to a more aggressive environment. The test uses high-alkali cement meeting an alkali content of 0.90% ± 0.10% and cement content of 420 $kg/m^3$ (708 $lbs/yd^3$). Moreover, sodium hydroxide is added to the mixing water to raise cement alkalis to 1.25%. A 75 mm x 75 mm x 285 mm (3 in. x 3 in. x 11.25 in.) test sample is prepared and cured in water for six months at 60°C (140°F). The same threshold percent expansion value as the CPT method is used to distinguish between non-reactive and reactive aggregates

### *Other Test Methods for Assessing the Reactivity of Different Aggregates*

Latifee [41] presented a chronological overview of major published test methods from 1940 to 2012, along with a critical comparative review of the prominent ones in his Ph.D. dissertation. The authors of this report have chosen not to include this content in the main part of the report. However, a summary of the discussions presented by Latifee has been added in **Appendix A** of this report.

### *Importance of a New Method to Determine Aggregate Reactivity*

For characterizing the aggregate reactivity, a new method was desired to eliminate the unreliable features (such as false positive and false negative results as well as long test duration) of currently available methods. Finally, in 2013 a new test method, call the Miniature Concrete Prism Test (MCPT) was developed by Rangaraju and Latifee at Clemson University [7] that addressed the limitations associated with the currently available methods. The primary objective behind their research effort was to develop a test method that would:

- Be shorter in duration compared to the 1-year long CPT (ASTM C1293) method;
- Subject the specimen to an environment that would not be as harsh as the one used in the AMBT (ASTM C1260 or AASHTO T 303) method, thereby reducing the chances of false positive results;
- give results that would have good correlation with aggregate performance in the field as far as ASR susceptibility is concerned;

- Not involve excessive crushing or grinding of the aggregates; avoiding the need for excessive crushing would help retain the original reactivity of the aggregates;
- Facilitate reliable assessment of different ASR mitigation methods without requiring excessive testing times.

The following section provides detailed discussions on the MCPT test procedure and its state of implementation across the United States.

## AASHTO TP 110: Miniature Concrete Prism Test, MCPT

### *Development of MCPT*

As already mentioned, the MCPT was developed through a research study sponsored by the Federal Highway Administration (FHWA) that focused on addressing the limitations associated with currently available ASR test methods. Later on, in 2014, the test method was adopted by the American Association of State Highway and Transportation Officials (AASHTO) as a standard test method and denoted as AASHTO TP 110-14. The AASHTO TP 110 test takes 56 days to complete, with an additional 28 days needed to test slow reacting aggregates. This testing method was found to provide good correlations with ASTM C1293 (1-year test) results as well as field performance. In addition, it was found to provide reliable and dependable results of aggregate susceptibility to ASR [7].

The MCPT uses a concrete prism of dimensions: 50 mm x 50 mm x 285 mm (2-in x 2-in x 11.25-in). A concrete prism expansion less than 0.04% after 56 days is considered acceptable in terms of ASR susceptibility, while an expansion above this value is considered reactive. The test specimens are placed in NaOH solution to accelerate the ASR mechanism. This method uses a cement content of 1.25%, similar to the CPT method. It also uses 12.5 mm (½-in) maximum coarse aggregate size rather than 19mm (¾-in) maximum size (used in CPT); no crushing of the aggregates is involved, unlike the AMBT method. A summary of the test conditions for the MCPT along with the evaluation criteria is presented below:

- Test duration: 8 weeks (56 days) or 12 weeks (84 days) depending on aggregate reactivity
- Test Temperature: 60.0 ± 1.7°C (140 ± 3°F).
- Specimen Type and Size: Prism – 50 mm x 50 mm x 285 mm (2 in. x 2 in. x 11.25 in.)
- Maximum coarse aggregate size: 12.5 mm (½ in.)
- Volume fraction of dry coarse aggregate in the concrete: 0.65 (fixed)
- Coarse Aggregate Proportion (% by weight) :
  - 12.5 mm – 9.5 mm: 57.5%
  - 9.5 mm – 4.75mm: 42.5%
- Fine Aggregate: Determined based on ACI 211; Absolute Volume Method
- Evaluation Criteria
  - Non-Reactive: If the prism expansion is less than 0.030% at 56 days or in between 0.031 to 0.040% with an average 2-week rate of expansion is less than 0.010% from 8 to 12 weeks period.

  - Reactive: If the prism expansion is greater than 0.040% at 56 days.

### *Recent Results from MCPT Testing in the USA*

Latifee and Rangaraju [7] evaluated the ASR susceptibility of 19 fine and coarse aggregates obtained from various sources using the newly developed MCPT method. They correlated the results with those from 14-day AMBT as well as 1-year CPT methods. The results showed that this method produced a strong correlation ($R^2 = 0.99$) with CPT and a relatively weaker correlation with the AMBT method ($R^2 = 0.5$) [7, 42].

Currently, the Montana Department of Transportation (MDT) is sponsoring a research study to assess the ASR susceptibility of different aggregate sources in Montana, as well as to quantify the extent of ASR-related damage in Montana. In their interim reports, the researchers have identified the MCPT as a promising test method, but also emphasize that this test method is still in its infancy, and therefore, more testing is required to check its accuracy and correlation with field performance of concrete [43].

### Existing Correlation between MCPT and both CPT and AMBT

Table 2 summarizes the criteria for classifying aggregates based on their ASR potential established through the AASHTO TP 110 (MCPT) protocol [11] ; these threshold limits were originally established during the development of MCPT test protocol at Clemson University. Similarly, Table 3 summarizes the different aggregate reactivity levels established using the two other test methods: CPT and AMBT as reported by Latifee [41]; these reactivity levels were adopted from the AASHTO PP 65 specification, titled "Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction" [44]. Latifee and Rangaraju (2014) [7] tested 12 aggregates from different sources using the three-test methods (AMBT, CPT, and MCPT). Their results indicated some discrepancy in the expansion results for three of the aggregates. For instance, one of the aggregate materials (QP) that was determined to be non-reactive using the 14-day AMBT method (the recorded expansion value was 0.080%, which is less than the threshold value of 0.10% specified by ASTM C1260), came out to be reactive upon testing using the 56-day MCPT and 1-year CPT methods. Conversely, two other aggregate types (SLC and MSP) exhibited opposite outcomes. In other words, both these aggregate types were determined to be non-reactive by MCPT and CPT methods, whereas the 14-day AMBT method found them to be reactive.

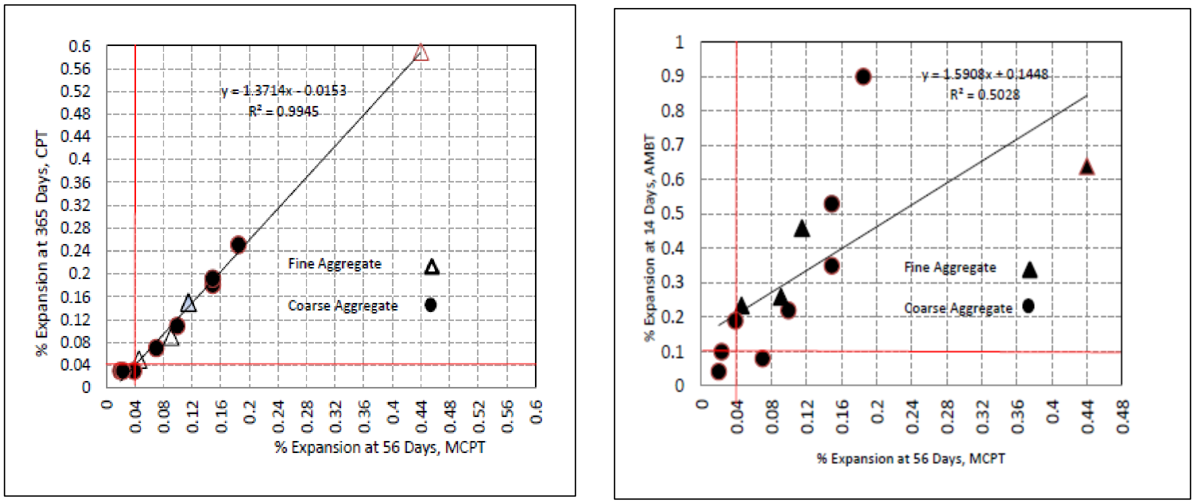
**Table 2. Criteria for Characterizing the Aggregate Reactivity in the MCPT Protocol [11]**

| Expansion at 56 Days, % (8 Weeks) | Average 2-Week Rate of Expansion from 56 to 84 Days, % ( 8 to 12 Weeks) | Degree of Reactivity |
|---|---|---|
| < 0.030 | N/A | Non-reactive |
| 0.031-0.040 | <0.010% per 2weeks | Non-reactive |
| 0.031-0.040 | >0.010% per 2weeks | Low/slow reactive |
| 0.041-0.120 | N/A | Moderately reactive |
| 0.121-0.240 | N/A | Highly reactive |
| >0.240 | N/A | Very highly reactive |

**Table 3. Classification of Aggregate Reactivity [41]**

| Reactivity Class | Description of Aggregate Reactivity | 1-Year Expansion in CPT, (%) | 14-Day Expansion in AMBT, (%) |
|---|---|---|---|
| R0 | Non-reactive | ≤ 0.04 | ≤ 0.10 |
| R1 | Moderately reactive | > 0.04, ≤ 0.12 | > 0.10, ≤ 0.30 |
| R2 | Highly reactive | > 0.12, ≤ 0.24 | > 0.30, ≤ 0.45 |
| R3 | Very highly reactive | > 0.24 | > 0.45 |

Figure 7 depicts the correlation between the 56-day MCPT results and the 1-year CPT as well as the 14-day AMBT results as reported by Latifee and Rangaraju [7]. An expansion threshold of 0.04% has been used with the MCPT (as well as CPT) results to distinguish the reactive and non-reactive aggregates. As seen from Figure 7a, excellent correlation ($R^2 = 0.99$) was observed between the MCPT and CPT test results. On the other hand, as seen from Figure 7b, the correlation between the MCPT and AMBT results was relatively weaker ($R^2 = 0.49$). Note that an expansion threshold of 0.10% was used with the AMBT test results to distinguish between reactive and non-reactive aggregates.



**(a)** **(b)**

**Figure 7. Correlation between MCPT and Other Test Methods (a) MCPT and CPT; (b) MCPT and AMBT** [7]

# Chapter 3

# Testing Materials and Protocols

## Introduction

This chapter presents details regarding the material selection procedure and test protocols followed to assess the ASR susceptibility of different Idaho aggregates. Fourteen (14) different aggregate materials with different characteristics and from different sources were selected for ASR susceptibility testing using the newly developed 56-day MCPT (AASHTO TP 110). Both the fine and coarse fractions of each aggregate material were tested independently to assess their ASR susceptibility. A non-reactive reference aggregate material was first identified for this purpose. When the coarse-fraction of a particular aggregate was being tested for ASR-susceptibility, non-reactive fine aggregates from the reference source were used in the concrete mix. Similarly, when the fine fraction of a particular aggregate was being tested for ASR susceptibility, non-reactive coarse aggregates from the reference source were used in the concrete mix. 14-day AMBT tests were also conducted on some of the aggregate materials to compare the results with the 56-day MCPT test results. Moreover, some of the aggregates were tested using the 1-year CPT method. The testing was carried out collaboratively at Boise State University and the University of Idaho. Some of the aggregates were selected for testing at both laboratories to check for inter-laboratory variations. The following section briefly describes the test methods considered in this study. Table 4 summarizes different test methods considered in this study to determine the ASR reactivity.

### *Accelerated Concrete Prism Test, ACPT*

This method is a modification of the ASTM C1293 test, and was originally proposed by Ideker et al. [39]. The idea is to reduce the test duration from 1-year to 6 months by subjecting the test samples to a higher curing temperature of $60^{o}$ C ($140^{o}$ F) compared to $38^{o}$ C ($100^{o}$ F) employed for CPT. The test procedure also uses high-alkali cement, meeting an alkali content of 0.90% ± 0.10% and cement content of 420 $kg/m^3$ (708 $lbs/yd^3$). Moreover, sodium hydroxide is added to the mixing water to raise cement alkalis to 1.25%. Similar to the 1-year test method, the ACPT samples have dimensions of 75 mm x 75 mm x 285 mm (3 in. x 3 in. x 11.25 in.). Change in specimen length is measured on the following days: 0, 3, 7, 14, 28, 56, 84, 112, 140, and 168. The same threshold percent expansion value as the CPT method is used to distinguish between non-reactive and reactive aggregates.

**Table 4. Details Regarding the Different ASR Test Procedures used in the Current Study**

| **Test Procedure** | **AMBT (ASTM C1260 or AASHTO T 303)** | **MCPT (AASHTO TP 110)** | **CPT (ASTM C1293)** |
|---|---|---|---|
| Test Type | Mortar Bar Test | Concrete Prism Test | Concrete Prism Test |
| Specimen Size | 1 in. x 1 in. x 10 in. | 2 in. x 2 in. x 10in. | 3 in. x 3 in. x 10 in. |
| Test Duration | 14 days | 56 to 84 days | 1 year |
| Storage Temperature | 80.0 ± 2.0° C<br>(176 ± 3.6° F) | 60.0 ± 1.7° C<br>(140 ± 3° F) | 38.0 ± 2.0 ° C<br>(100.4 ± 3.6 ° F) |
| Storage Environment | In NaOH solution | In NaOH solution | 100% $H_20$ |
| Initial Curing | 24hrs in $H_20$ @ 80 °C | 24hrs in $H_20$ @ 60 °C | N/A |
| Cement Quantity | 420 kg/m$^3$ (26lb/ft$^3$) | 420 kg/m$^3$ (26lb/ft$^3$) | 420 kg/m$^3$ (26 lb/ft$^3$) |
| Cement Alkali Content | 0.60 % $Na_2Oeq$ | 0.9 ± 0.1 % $Na_2Oeq$ | 0.9 ± 0.1 % $Na_2Oeq$ |
| Alkali Boost | No Alkali boost | 1.25% $Na_2Oeq$ | 1.25% $Na_2Oeq$ |
| Coarse Aggregate | 4.75mm – 0.15mm | 12.5 mm (1/2 in.) | 19mm – 4.75mm |
| Water-to-Cement Ratio | 0.47 – 0.50 | 0.45 | 0.42 – 0.45 |
| Dry volume fraction of coarse aggregate | N/A | 0.65 | 0.70 |

## Aggregate Selection

### *Selection Criteria*

Three major criteria were considered for selecting the test aggregates during this study: 1) Aggregates with different mineralogical compositions; 2) Aggregates with prior test results from ASTM C1293 and/or ASTM C1260 (AASHTO T 303); and 3) Aggregates identified as being susceptible to ASR by both or either of the two commonly used test methods (ASTM C1260 or AASHTO T 303 and ASTM C1293), and those with contradictory test results from both tests. During a prior research study sponsored by ITD (RP 212: Lithological Characterization of Active ITD Aggregate Sources and Implications for Aggregate Quality), Gillerman and Weppner [28] collected three bags for each aggregate material tested. Among the three bags, they used two bags, and archived the third back as “reserved”. These bags provided an excellent source of material for the current research study. Not only were the aggregates already investigated for their lithologic characteristics, but ASR susceptibility test results (per ASTM C1260, and in some cases ASTM C1293) were also available for most of the aggregate materials. The research team worked with ITD personnel to retrieve these bags from ITD storage for use in the current project. Note that most of these sources represent aggregates used frequently in different ITD projects.  Table 5 lists the location and district information for the different aggregates retrieved from the RP 212 material archives.

**Table 5. Aggregate Materials Retrieved from RP 212 Material Archives for Potential use in the Current Research Study**

| Idaho District | Sample ITD Name | Location Description |
|---|---|---|
| D1 | BY-74c | Near Kootenai River, North of Bonners Ferry, ID |
| | Kt-213c | Rathdrum Prairie, Northwest of Coeur d'Alene, ID |
| | PSC-173c | Near the Spokane River, east of Spokane, WA |
| D2 | ID-121c | Near Salmon River, South of Whitebird Pass, ID |
| | NP-82c | Near Snake River, Below Confluence with Clearwater River, Lewiston, ID |
| D3 | CN-140c | Near Boise River, Northwest of Caldwell, ID |
| | EI-116c | East of Bliss, ID, King Hill |
| | ORE-8c | Near Snake River, Within City Limits of Ontario, OR |
| D4 | LN-80c | East of SH-75, North of Shoshone, ID |
| | Md-45c | On Snake River, Southeast of Acequia, ID |
| D5 | Bg-111c | West of Blackfoot, Idaho |
| | Pw-84c | West of Chubbuck, Idaho |
| D6 | Bn-155c | Near Snake River, South of Idaho Falls, ID |
| | Le-154c | On the Salmon River, North of Salmon and South of Carmen, ID |
| | Ma-22c | Near Teton River, North Side of Rexburg, ID (Within the City Limits) |

Similarly, another aggregate material (denoted in this report as Agg-5; Rock type: Granite) was collected for potential use as a non-reactive aggregate source. AMBT test results for this material confirmed its non-reactive nature, and therefore, it was used as the reference aggregate material throughout this study. Table 6 lists the location information for these additional aggregate materials tested in the current study. Note that four of these additional aggregate materials were obtained from quarries outside the state of Idaho. It is therefore likely that some of these aggregates may not be commonly used in the state of Idaho for concrete applications (depending on the proximity of the source to the project under consideration). These aggregates were included in the test matrix to compare their ASR susceptibility levels assessed by the MCPT as well as other test methods (e.g., AMBT, CPT, ACPT) .

**Table 6. Additional Aggregate Materials Collected to use in the Current Research Study**

| Aggregate ID | Location Description |
|---|---|
| Wn-56 | Idaho District 3 Basalt quarry |
| Agg-1 | Idaho District 1 and part of Washington |
| Agg-2 | Igneous rock; out of state |
| Agg-3 | Sedimentary rock; out of sate |
| Agg-4 | Eastern Washington, out of state |
| Agg-5 | Idaho District 1 and part of Washington |

Not all reserved aggregate bags collected from the ITD RP 212 material archives contained enough quantity of aggregates to perform the required testing in the current study. Collecting more aggregate of the same kind was not feasible within the timeframe of the project. Besides the aggregate samples collected from RP 212 material archives, the research team also collected additional aggregate types with potential ASR susceptibility. Testing of these additional aggregates was primarily undertaken at the University of Idaho laboratories. Table 7 lists the final set of aggregates tested for ASR susceptibility in the current study. Note that the material designated as Wn-56 was initially collected to be used as a reference aggregate. However, 14-day AMBT tests indicated that this aggregate (Wn-56) was ASR-susceptible. Therefore, it was included in the test matrix as another material source being evaluated.

**Table 7. Aggregate Materials used for ASR Testing in the Current Study**

| Reserved Aggregates from ITD RP 212 | From other Sources |
|---|---|
| El-116c | Wn-56 |
| ORE-8c | Agg-1 |
| Md-45c | Agg-2 |
| Ln-80c | Agg-3 |
| Bg-111c | Agg-4 |
| Bn-155c | Agg-5 |
| Ma-22c | - |
| Pw-84c | - |

Each aggregate type was fractionated to separate the Coarse Aggregate (C.A) and Fine Aggregate (F.A) fractions. The objective was to separately assess the ASR susceptibilities of the coarse and fine fractions for each aggregate source. When C.A was tested, the F.A fraction came from the reference aggregate and vice versa. Note that the AMBT method requires the use of fine aggregates only (the coarse aggregates are crushed to sizes below 4.75 mm).

## Reference Aggregate Selection

According to the AASHTO TP 110 standard, a reference aggregate is needed to assess the ASR susceptibility of any potential reactive aggregate. Technically, any aggregate material that is not reactive from an ASR consideration, can be used as a reference aggregate. Identifying a non-reactive reference aggregate source is essential to discern moderately reactive aggregates accurately. Similarly, accurate determination of the effectiveness of mitigation measures also depends on the reference aggregate. In this project, the AMBT method (ASTM C1260 or AASHTO T 303) was first used to identify and select a reference aggregate to be used during the remainder of the study. This specific test method was chosen because it subjects the aggregate to harsh testing conditions, and even slightly reactive aggregates are likely to be identified through this test. Although the AMBT test has been known to give false-positive results on several instances, such an error would only result in a conservative approach as far as selection of the reference aggregate is concerned. Multiple aggregate materials were tested in an effort to identify the reference aggregate. The candidate reference aggregate materials were tested both at Boise State as well as University of Idaho laboratories. Although the WN-56 (basalt) material was selected as a potential reference aggregate after discussion with ITD personnel, the 14-day AMBT tests indicated this aggregate to be highly reactive (expansion of the mortar bars was recorded to be 0.45% at 14 days; the threshold to separate reactive and non-reactive aggregates per the AMBT method is 0.10%). These results were verified by repeated testing at both the Boise State as well as University of Idaho laboratories. The next aggregate source considered for potential use as reference aggregate was: TF-25 in District 4 (near Hollister on US-93 south of Twin Falls). Three aggregate types (Dolomite, Quartz, and Lemhi) were collected from this source and were tested at the ITD central lab using the 14-day AMBT method. The test results confirmed all three aggregate types to be reactive; therefore, the research team was forced to continue the search for a suitable reference aggregate. Finally, a Granite source in Lewiston (ITD District 2) rendered aggregates that were found to be non-reactive through 14-day AMBT testing at both the university laboratories. The AMBT testing was performed multiple times as the Granite was collected from different layers at the quarry. All test results confirmed the material to be non-reactive in terms of ASR susceptibility. Table 8 lists the 14-day AMBT results for all aggregate materials considered as candidates for use as the reference aggregate. As seen from the table, only the granite material was found to be non-reactive for ASR considerations. As already mentioned, the WN-56 material was observed to be highly reactive; sufficient quantity of this material had already been collected by the researchers for use in this study. Therefore, it was added to the test matrix as another aggregate source that was evaluated for ASR susceptibility using different test methods.

**Table 8. 14-Day AMBT Results for Different Aggregate Sources Considered for Potential Use as Reference Aggregates**

| Sample Tested (Laboratory) | AMBT bar Expansion at 14-Days (%) | Check Reactivity |
|---|---|---|
| Wn-56 (BSU-1) | 0.616 | Reactive |
| Wn-56 (BSU-2) | 0.642 | Reactive |
| Wn-56 (UoI) | 0.518 | Reactive |
| Dolomite (ITD) | 0.187 | Reactive |
| Quartz (ITD) | 0.198 | Reactive |
| Lemhi (ITD) | 0.381 | Reactive |
| Agg-5 (BSU) | 0.001 | Non-reactive |
| Agg-5 (UoI-1) | 0.075 | Non-reactive |
| Agg-5 (UoI-2) | 0.009 | Non-reactive |

## Material Processing and Fractionation

Before the selected aggregates could be used for ASR testing, they were crushed to suitable sizes, and fractionated into different proportions. The crushing was carried out at the ITD central laboratories, and fractionation was carried out at the Boise State laboratory. Similarly, some of the additional aggregate types selected for testing were processed at the University of Idaho laboratories. Table 9 shows the fine aggregate (FA) grading requirement prescribed by AASHTO T 303 and ASTM C1260 (AMBT) standards that meeting the ASTM C33 specification [45]. The fineness modulus (FM) of that gradation was found to be 2.90 According to AASHTO TP 110 (MCPT) and ASTM C1293 (CPT) methods, to determine the ASR reactivity of coarse fraction, a non-reactive fine aggregate source should be used with a fineness modulus (FM) of 2.6 ± 0.3 and 2.7 ± 0.2 respectively. The fine aggregate materials considered for MCPT and CPT testings were graded in accordance with the gradation requirement of AMBT standard. It was done because the fineness modulus (FM) of that gradation is within the limit suggested by MCPT and CPT standards.

**Table 9. Fine Aggregate Grading Requirements**

| Sieve Size | | Mass (%) |
|---|---|---|
| Passing | Retained on | |
| 4.75 mm (No. 4) | 2.36 mm (No. 8) | 10 |
| 2.36 mm (No. 8) | 1.18 mm (No. 16) | 25 |
| 1.18 mm (No. 16) | 600 µm (No. 30) | 25 |
| 600 µm (No. 30) | 300 µm (No. 50) | 25 |
| 300 µm (No. 50) | 150 µm (No. 100) | 15 |

AMBT method does not involve the use of any coarse aggregate while casting the mortar bars; the nominal maximum size used in AMBT testing is 4.75 mm. Unlike AMBT testing, the MCPT and CPT testing require coarse aggregate (CA) fractions and have a specific requirement for the gradation as well as volume proportion to run the test. In both test methods, the coarse aggregates volume required is 65% of total concrete volume. Table 10 shows the gradation and percentage mass of coarse aggregate (CA) recommended by MCPT and CPT test methods. It should be noted that the individual mass percentages shown in Table 9 and Table 10 for each sieve size are the percentage of respective aggregate's (FA or CA) total mass, not the percentage of the entire concrete weight.

**Table 10. Coarse Aggregate Grading Requirements**

| Test Name | Sieve Size | | Mass (%) |
|---|---|---|---|
| | Passing | Retained on | |
| MCPT | 12.5mm (1/2 in.) | 9.5 mm (3/s in.) | 57.5 |
| | 9.5 mm (3/8 in.) | 4.75 mm (No. 4) | 42.5 |
| CPT and ACPT | 19.0-mm (3/4-in.) | 12.5-mm (1/2-in.) | 33 |
| | 12.5-mm (1/2-in.) | 9.5-mm (3/8-in.) | 33 |
| | 9.5-mm (3/8-in.) | 4.75-mm (No. 4) | 33 |

## Division of Test Matrix between the Two University Laboratories

As already mentioned, this project was carried out in collaboration between researchers from Boise State University and the University of Idaho. This collaboration was critical as it significantly enhanced the subject knowledge as well as the testing facilities available to be used in this project. Dividing the laboratory tests among the two university laboratories also facilitated inspection of the inter-laboratory variability in the test results. Although the primary focus of the project was to perform the 56-day MCPT test on selected aggregate materials, the test matrix also included performance of the at 14-day AMBT as well as the 1-year CPT methods. A total of 8 reserved aggregate samples (listed in Table 7) were retrieved from the ITD RP 212 material archives. Besides randomly assigning different aggregate materials to be tested at one of the two laboratories, multiple aggregate materials were assigned to be tested at both laboratories to identify any significant inter-laboratory variation. Note that the number of tests that could be run on each material was largely governed by the quantity of aggregates available in the material archives. First, approximate aggregate quantities required to run a single MCPT test was established, and was compared with the quantity of aggregates available to determine whether or not sufficient material quantities were available for multiple replicate testing, inter-laboratory verification testing, as well testing using other methods (such as the 14-day AMBT and 1-year CPT). Initial calculations on the material quantities indicated that sufficient material was not available for multiple MCPT tests at both university laboratories for several of the reserved aggregate types retrieved from the RP 212 material archives. In such cases, those particular aggregate materials were tested in one laboratory only. Conversely, some of the other aggregate materials were available in sufficient quantities to enable multiple replicates at both laboratories to check for inter-laboratory variations. Table 11 lists the aggregates tested at each university laboratory following the MCPT method. As mentioned earlier, in addition to aggregates retrieved from the RP 212 material archives, a large quantity of the Wn-56 material was collected, and was later added to the test matrix. The reference aggregate (Agg-5) was also included in the test matrix and tested at the University of Idaho laboratory.

**Table 11. List of Aggregate Materials Tested at the Two University Laboratories**

| Boise State University | University of Idaho |
|---|---|
| EI-116c* | EI-116c* |
| ORE-8c* | ORE-8c* |
| Md-45c* | Md-45c* |
| Ln-80c | Ma-22c |
| Bg-111c | Pw-84c |
| Bn-155c | Wn -56 |
| Wn-56 | Agg-5** |
| * overlapped<br>** reference aggregate | |

Moreover, four additional aggregate materials (Agg-1, Agg-2, Agg-3, and Agg-4) were also tested for ASR susceptibility at the University of Idaho. Table 12 lists all aggregate types tested under the scope of the current study, and identifies the different tests that were run on each aggregate type.

**Table 12. List of All Aggregates Tested in the Current Study, and the Tests Carried Out on Each**

| Aggregate Name | AMBT (14-days) | MCPT (56-days) | CPT (1-year) |
|---|---|---|---|
| El-116c | ✓ | ✓ | - |
| ORE-8c | ✓ | ✓ | - |
| Md-45c | ✓ | ✓ | - |
| Ln-80c | - | ✓ | - |
| Bg-111c | - | ✓ | - |
| Bn-155c | - | ✓ | - |
| Ma-22c | ✓ | ✓ | - |
| Pw-84c | ✓ | ✓ | - |
| Wn-56 | ✓ | ✓ | ✓ |
| Agg-1 | ✓ | ✓ | ✓ |
| Agg-2 | ✓ | ✓ | ✓ |
| Agg-3 | ✓ | ✓ | ✓ |
| Agg-4 | ✓ | ✓ | ✓ |
| Agg-5 | ✓ | ✓ | ✓ |

## Laboratory Test Set-Up

Civil Engineering material laboratories at both Boise State as well as University of Idaho were equipped to run tests required for successful completion of this project. The objective was to set-up parallel testing facilities at both labs so that multiple materials could be tested at the same time. Figure 8 shows photographs of some of the testing apparatus used in the current study.

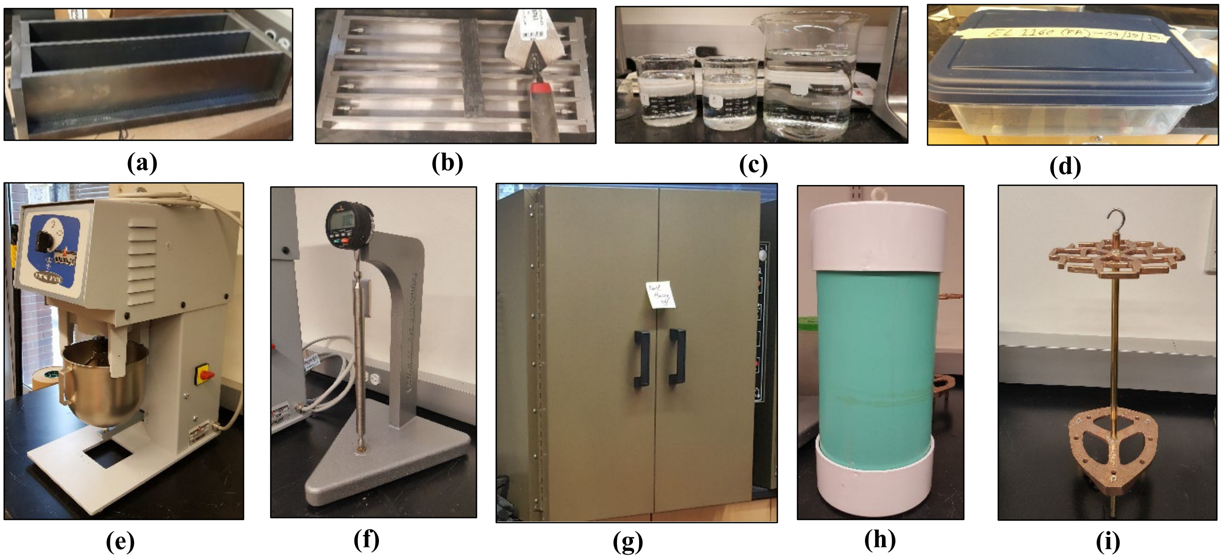


**Figure 8. Laboratory Test Set-Up. (a) MCPT Steel Molds; (b) AMBT Steel Molds; (c) Glass Beaker; (d) Plastic Container for Curing; (e) Mortar Mixer; (f) Digital Length Comparator; (g) Laboratory Oven; (h) Mortar Bar Container; (i) Mortar Bar Stand.**

## Portland Cement

Both low-alkali and high-alkali cement were used in this project to run the AMBT and MCPT tests, respectively. The low-alkali cement was collected from two different sources: (1) Ashgrove Cement Plant in Durkee, Oregon (Cement Type: I/II/IV); and (2) Pre-Mix Concrete Plant in Pullman, Washington (ASTM C150 Type I). The equivalent alkali content for both the low-alkali cement sources was 0.49% $Na_2Oeq$. The high-alkali cement (ASTM C150 Type I) was acquired from Illinois Cement Company, LaSalle, IL. The equivalent alkali (NaEQ) content was 0.82% $Na_2Oeq$, which falls in the required alkali content range (0.9 ± 0.1 percent $Na_2Oeq$) specified in the AASHTO TP 110 standard with Blaine's fineness of 383 $m^3/kg$. The autoclave expansion of both low-alkali and high alkali cement was 0.03% and 0.018%, respectively, which is well below 0.8% requirement. The specific gravity is 3.15 for both cement types. Table 13 lists the chemical composition of the three cement sources used in the current study. It should be noted that, although universities used low alkali cement collected from different sources, it would not affect the test results remarkably, as the equivalent alkali content is the same. Moreover, the ASTM C1260 standard clearly states that *"The alkali content of the cement has been found to have negligible or minor effects on expansion in this test."*

**Table 13. Chemical Composition of Different Cement Types used during Laboratory Testing**

| **Cement type** | **Chemical Composition by Mass (%)** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **$SiO_2$** | **$Al_2O_3$** | **$Fe_2O_3$** | **CaO** | **MgO** | **$SO_3$** | **NaEQ** |
| Low-Alkali Cement (Durkee, OR) | 21.58 | 3.39 | 3.10 | 62.64 | 4.60 | 2.03 | 0.49 |
| Low-Alkali Cement (Pullman, WA) | 20.60 | 5.10 | 3.40 | 64.50 | 1.00 | 3.10 | 0.49 |
| High-Alkali Cement | 19.45 | 4.85 | 3.13 | 61.84 | 2.92 | 4.15 | 0.82 |

## Reagent

Reagent grade sodium hydroxide (NaOH) beads were mixed into the curing water to prepare a 1 N (Normality = 1) curing solution. Although the NaOH beads used at the two university laboratories were obtained from two different vendors, the chemical compositions were identical. The same reagent was also used to increase the alkali level of MCPT concrete samples to 1.25% $Na_2Oeq$ by weight of cement. Note that 1N of NaOH is equivalent to 40g of NaOH. Figure 9 shows a photograph of the NaOH beads used in the current study.

**Figure 9. Photograph Showing Sodium Hydroxide (NaOH) beads used during Laboratory Testing**

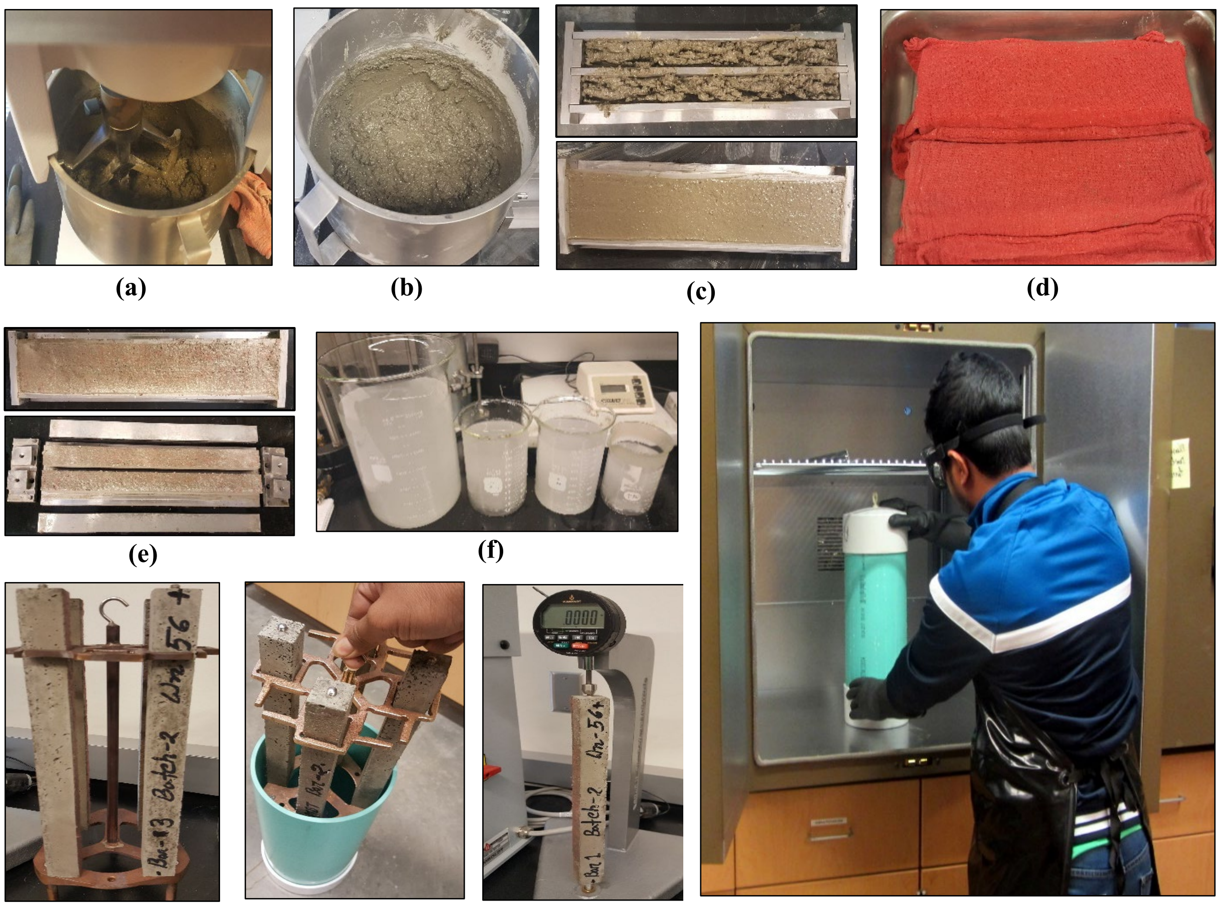
## Mix Design and Specimen Preparation

### *AMBT Method*

For the 14-AMBT method, three replicates of the 1 in x 1 in x 10 in (25 mm x 25 mm x 250 mm) specimens were prepared following the ASTM C1260 standard. Prior to mixing, aggregates (fine) were washed, oven-dried, and then sieved and batched to meet the gradation requirements listed in Table 9.

The ASTM C1260 (AASHTO T 303) standard specifies the amount of aggregate (990 g) and cement required to make three mortar bars. The standard also suggests using a water-cement ratio of 0.47 (ASTM C1260) or 0.50 (AASHTO T 303); this helps determine the amount of water to be added, since the amount of cement is already known. The mortar was prepared using a mortar mixer, which conforms to the requirements of AASHTO T 162 (ASTM C305-99) [46, 47] standards. The mixing was carried out to ensure the mortar was uniform, and did not show any signs of segregation.

The mix was then placed into steel molds in two approximately equal layers, and each layer was compacted with a small tamper. The mortar bars were then covered with a wet towel (to prevent moisture loss), and were left for 24 hours. All subsequent test steps, such as: (1) demolding of the bars; (2) taking the zero reading; (3) initial curing in water; (4) preparation of NaOH solution; (5) curing in the NaOH solution at a fixed temperature; and (6) recording the bar lengths on specific days, were all carried out per the ASTM C1260 specifications. Figure 10 shows photographs of different steps during the AMBT testing.



(a) (b) (c) (d)

(e) (f)

(g) (h) (i) (j)

**Figure 10. Photographs Showing Different Steps during AMBT Testing: (a) Mixing of the Mortar; (b) Mortar After the Mixing. (c) Pouring the Mortar and Preparation of the Mortar Bars; (d) Hardening of Bars Covered with a Wet Towel. (e) Demolding of Mortar Bars; (f) Preparation**

### *MCPT Method*

MCPT concrete prism bars of dimensions 50 mm x 50 mm x 250 mm (2 in. x 2 in. x 10 in.) were prepared in accordance with AASTHO TP 110 and ACI concrete mix design [11, 48] specifications. Some of the mix design parameters, such as the water cement ratio (0.45) and the coarse aggregate volume fraction (0.65) were specified in the AASHTO TP 110 standard. The amount of concrete required to prepare three MCPT bars could be established easily. However, before the concrete mix could be designed, it was important to first determine the bulk density (dry unit weight) of the coarse aggregate fraction; this was accomplished using the rodding method described in ASTM C29/C29M [49]. Figure 11 shows photographs of the coarse aggregate dry density measurement set-up used in the current study. The bulk density tests were carried out at both the university laboratories for all the aggregates being tested for ASR susceptibility.

(a) (b) (c)

**Figure 11. Coarse Aggregates Bulk Density (Unit Weight) Test (a) Cylindrical Measure and Tamping Rod; (b) Measure Filled with Aggregates; (c) Determination of the Mass of the Measure and Aggregates**

Table 14 summarizes the bulk density test results of the selected aggregate types tested at Boise State University and University of Idaho. The mix design involved two primary steps: 1) determination of the proportion, and 2) the actual weight of ingredients of the concrete. Firstly, the total volume of concrete, cement, water, and coarse aggregates (C.A) was calculated considering a reasonable percent waste using the known bar size, w/c ratio, and volume of coarse aggregate to volume of concrete ratio. After that, the volume of fine aggregate was determined using the ACI mix design absolute volume method; by deducting the volume of cement, water, coarse aggregate and the volume of entrapped air content. The approximate entrapped air content was obtained from Table 6.3.3 of the ACI concrete mix design method [47] considering the concrete mix as non-air-entrained concrete.

**Table 14. Bulk Density (Unit Weight) of Aggregate Samples tested at Boise State University and the University of Idaho**

| Testing Laboratory | Sample Name | Aggregate Size (mm) | Dry Unit Weight (kg/m$^3$) | Dry Unit Weight (lb/ft$^3$) |
|---|---|---|---|---|
| Boise State University | CN-140 C | 9.50 | 1518.3 | 94.8 |
| | | 4.75 | 1502.7 | 93.8 |
| | BG-111C | 4.75 | 1592.4 | 99.4 |
| | EL-116C | 4.75 | 1402.8 | 87.6 |
| | Wn-56 | 9.50 | 1645.8 | 102.7 |
| | | 4.75 | 1634.2 | 102.0 |
| | Agg-5 | 9.50 | 1738.0 | 108.5 |
| | | 4.75 | 1671.0 | 104.3 |
| University of Idaho | EI-116c | 4.75 | 1403.1 | 87.6 |
| | ORE-8c | | 1568.3 | 97.9 |
| | Md-45c | | 1557.4 | 97.2 |
| | Pw-84c | | 1531.1 | 95.6 |
| | Ma-22c | | 1566.4 | 97.8 |

| | | | | |
|---|---|---|---|---|
| | Wn-56 | | 1612.4 | 100.6 |
| | Agg-1 | | 1503.7 | 93.8 |
| | Agg-2 | | 1585.5 | 98.9 |
| | Agg-3 | | 1700.3 | 106.1 |
| | Agg-4 | | 1592.0 | 99.39 |
| | Agg-5 | | 1634.3 | 102.0 |

As the next step, the required weights for each material were calculated using their corresponding volume fractions and unit weights. Note that the unit weight of the fine aggregate was unknown. Therefore, the total weight of all other ingredients (except the fine aggregate) was deducted from the total weight of the concrete to find the mass of required fine aggregate. A similar procedure was followed while designing the concrete mix for the 1-year CPT test with a prescribed water-cement ratio of 0.45.

The MCPT testing involves the use of high-alkali cement, meeting an alkali content of 0.90% ± 0.10%. In addition to that, NaOH beads were added to the concrete mixing water to raise cement alkalis to 1.25%. According to AASHTO TP 110, 1.898 kg/m$^3$ NaOH is required to achieve a total alkali content of 1.25 percent of $Na_2O$ in 1 cubic meter of concrete. From this information, the amount of NaOH needed for three MCPT bars was determined. A typical example mix design spreadsheet is provided in **Appendix B**.

Once the mix design parameters were finalized, the concrete was mixed into two equal batches for each test, and was then poured into the molds and compacted with a regular tamping rod. The subsequent steps involved in the test were carried out per AASHTO TP 110 specifications. As mentioned earlier, the MCPT method requires 56-84 days to determine the ASR susceptibility of a particular aggregate material. Twelve parallel test set-ups were operational (including both the university laboratories) to expedite the testing phase of the project, and reduce the overall time required to complete the project tasks. Figure 12 and Figure 13 show photographs of different steps involved in the MCPT method; Figure 12 shows photographs from the Boise State laboratory, whereas photographs included in Figure 13 were taken at the University of Idaho.

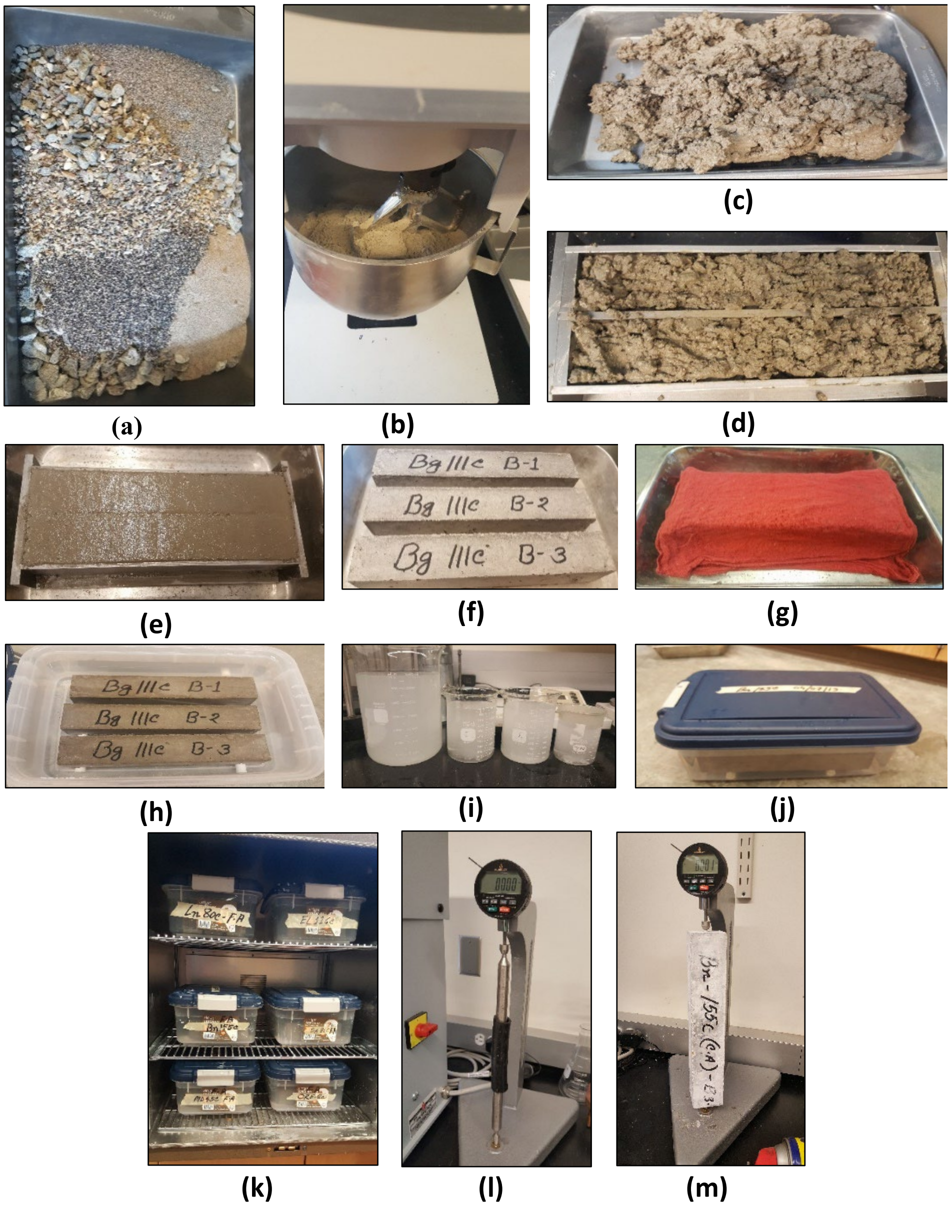
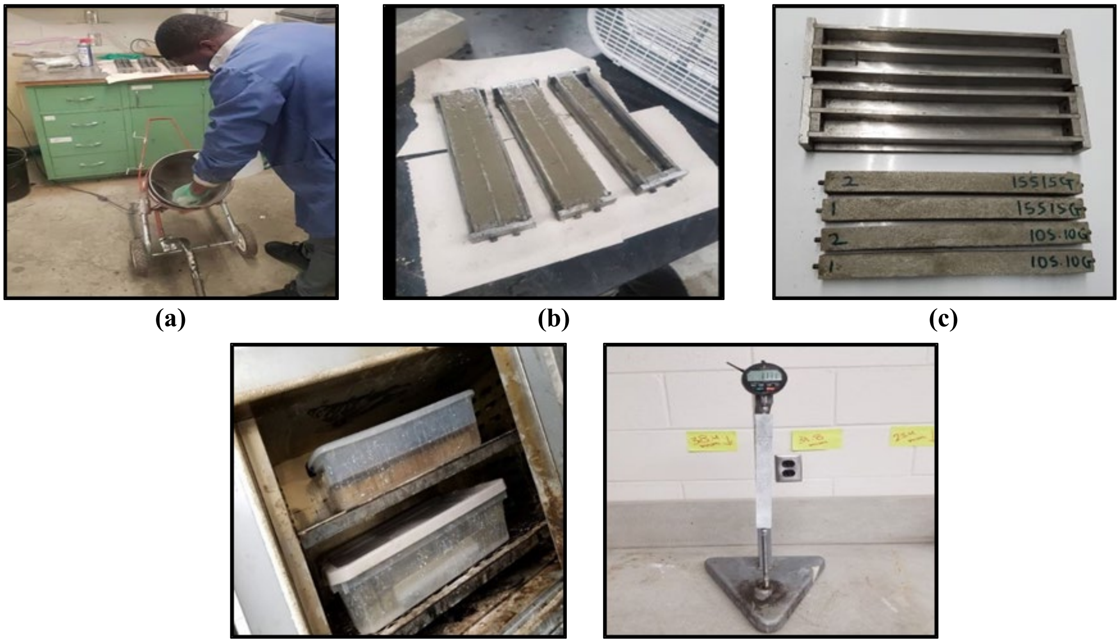


**Figure 12. Photographs from the Boise State Laboratory Showing Different Steps involved in the MCPT: (a) Aggregate Preparation; (b) Concrete Mixing;; (c) Concrete After Mixing; (d) Pouring Concrete into the Molds; (e) Preparation of Concrete Bars; (f) Demolding of Concrete Bars; (g) Concrete Bars Wrapped in a Wet Towel; (h) Curing in Water; (i) Preparation of NaOH solution; (j) Curing in the NaOH Solution; (k) Sample Placed in the Oven; (l) Length Measurement of Reference Bar; (l) Length Measurement of Prism Bars Using the Digital Length Comparator.**



(a) (b) (c)

(d) (e)

**Figure 13. Photographs from the University of Idaho Laboratory Showing Different Steps involved in the MCPT: (a) Mixing and Preparation of Concrete; (b) Pouring Concrete in the Molds and Preparation of the Bars; (c) Demolding the Concrete Bars; (d) Sample Placed in the Oven for Curing; (e) Expansion Measurement Using Digital Length Comparator.**

## Deformation Measurement

The length change of test samples was measured to assess ASR potential in accordance with ASTM C 490 [50]. After each test specimen was prepared and cured under the respective test method specifications, a length comparator was used to measure the change in specimen length at the pre-defined age. A digital length comparator was used for this purpose. A reference bar reading was taken each time before measuring the specimen lengths. Figure 14 shows the equation used to calculate the change in length at any age (x days).

$$L\% = \frac{Lx - Li}{G} \text{ x } 100$$

**Figure 14 Equation to Determine the Length Change.**

Where,

L = Change in Length at x age in %,

Lx = Comparator reading of test specimen at x-age minus comparator reading of reference bar at x age (in inches)

Li = Initial comparator reading of specimen minus comparator reading of reference bar at that time (in inches)

G = Nominal Gauge Length (10 inches).

The calculated change in specimen length is expressed to the nearest 0.001%, and the average values are expressed to the nearest 0.01%. Figure 15 shows photographs of the specimen length change measurement for the different tests carried out under the scope of the current study.

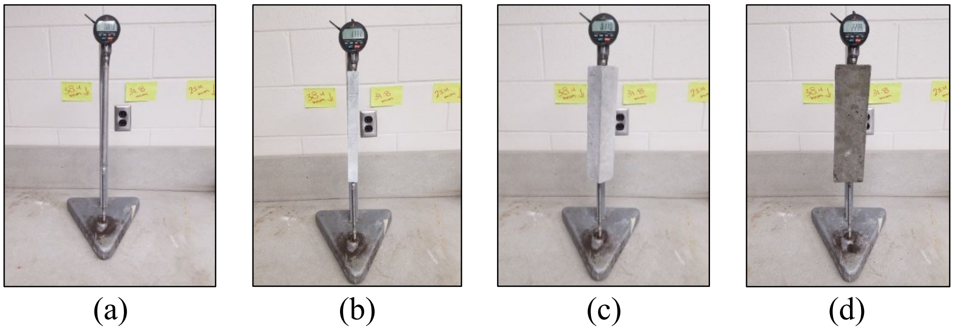


**Figure 15. Length Change Measurement. (a) Reference Bar; (b) AMBT Sample; (c) MCPT Sample; and (d) CPT sample**

Data obtained from the laboratory testing will be presented and analyzed in the next chapter of this report.

# Chapter 4
# Evaluation of Aggregates ASR Potential

## Introduction

As discussed in the previous chapter, the ASR potential of test aggregates was evaluated mainly using 56-day MCPT. In addition, 14-day AMBT, 1-year CPT, and 6-month ACPT were conducted on selected test aggregates. Furthermore, 14-day AMBT test results were obtained from ITD database for some test aggregates. Data from all of these tests have been presented in this section.

## 56-Day MCPT Test Results (AASHTO TP 110)

As mentioned earlier, the primary objective of this research study was to assess the ASR susceptibility of Idaho aggregates using the newly developed AASHTO TP 110 test method (also known as the 56-day Miniature Concrete Prism Test). Aggregate materials collected from across the state of Idaho were tested at both Boise State University and University of Idaho. Results obtained from these tests have been presented in Figures 16 through 19. Figure 16 and Figure 17 show the 56-day MCPT results for the coarse and fine aggregates tested at the Boise State laboratory. The coarse and fine fractions for seven different aggregate materials were tested at the Boise State laboratory. As seen from Figure 16, the percent expansion values recorded for the coarse aggregate fractions for all the seven aggregate materials exceeded the pre-established (by AASHTO TP 110) threshold value of 0.04%. The lowest expansion (0.05%) was recorded for the material designated as Ln-80c., which was a volcanic rock obtained from ITD District 4 [28]. Interestingly, Wn-56, which was originally selected as a candidate reference aggregate source, exhibited the highest expansion (0.26%) during MCPT. As already mentioned, an aggregate sample is considered to be very highly reactive when the expansion at the end of the test is higher than the standard limit of 0.241%. Results presented in Figure 16 also reveal that coarse fractions for three of the aggregate materials (Md-45c, Bn-155c, and Ln-80c) were found to be moderately reactive, with recorded 56-day expansion values of 0.07%, 0.12%, and 0.05%, respectively. The coarse fractions of El-116c (District 3; Elmore County), ORE-8c (District 3), and Bg-111c (District 5; Bingham County) were all found to be highly reactive with 56-day expansion values of 0.14%, 0.15%, and 0.17%, respectively; the threshold expansion value used by AASHTO TP-110 to separate moderately- and highly- reactive aggregates is: 0.12%.

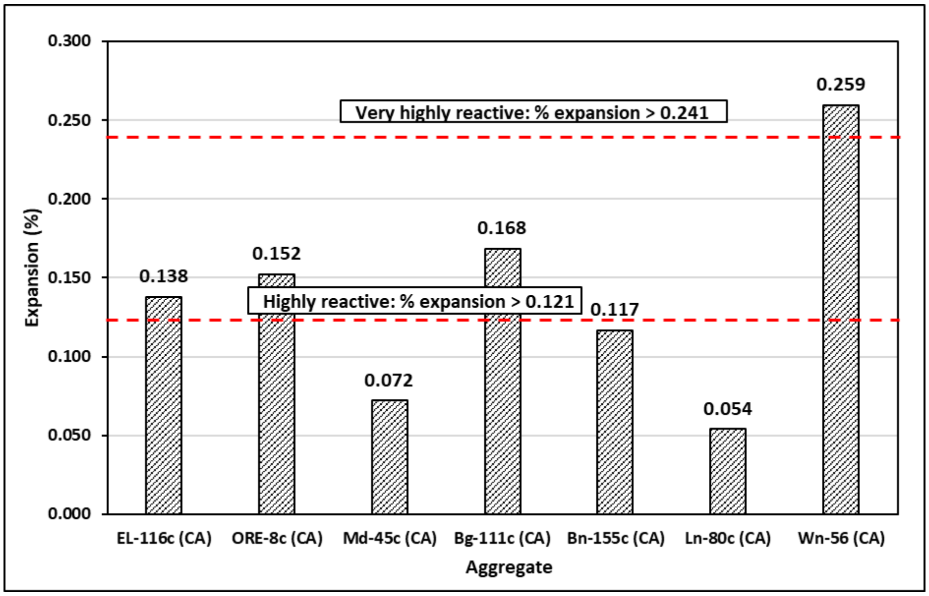


**Figure 16. 56-Day (MCPT) Expansion Values for Coarse Aggregate Fractions of the Materials Tested at Boise State University**

Figure 17 shows test results corresponding to the fine fractions of the same aggregate materials. Similar to the results for the coarse fractions, the fine fractions for none of the tested aggregates exhibited expansion values less than 0.04%. Moreover, the expansion values corresponding to the fine fractions of all the aggregate materials fall in the “very highly reactive’ category defined by AASHTO TP 110 (Expansion > 0.241%)

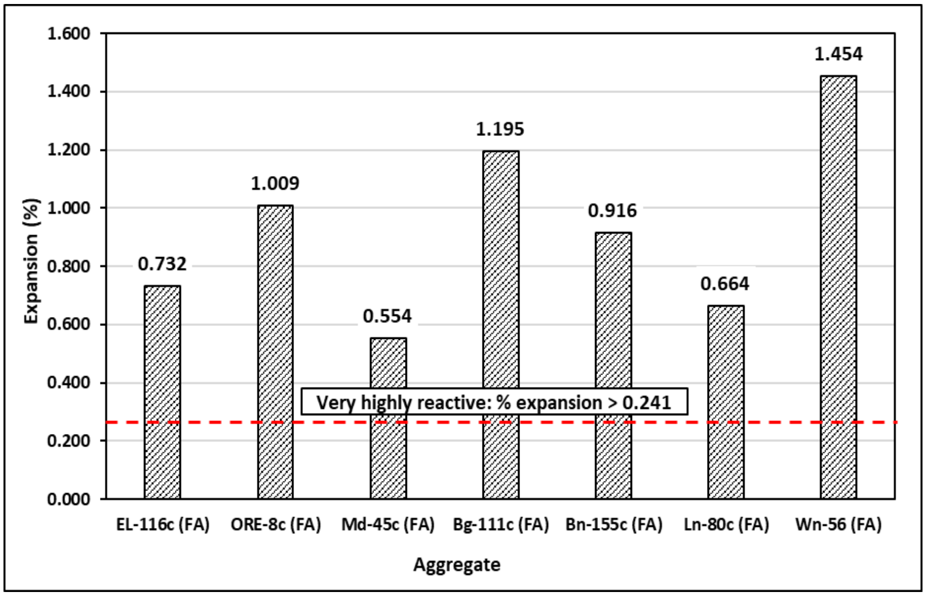


**Figure 17. 56-Day (MCPT) Expansion Values for Fine Aggregate Fractions of the Materials Tested at Boise State University**

Similar tests were run at the University of Idaho on nine (9) coarse aggregate fractions, and eleven (11) fine aggregate fractions; the results have been presented in Figure 18 and Figure 19, respectively. The results show that all the coarse aggregate fractions, except for Agg-5 (granite) that was used as a reference aggregate throughout this study, exceed the 0.04% non-reactive expansion threshold; the value recorded for the coarse fraction of Agg-5 was 0.025%. Four of the aggregate materials ( Ma-22c, Agg-2 (Basalt), Wn-56 and Agg-3 (Limestone)) can be categorized as being 'moderately reactive' with recorded expansion values less than 0.12%. The ORE-8c, Md-45c, Pw-84c materials belong to the 'highly-reactive' category.

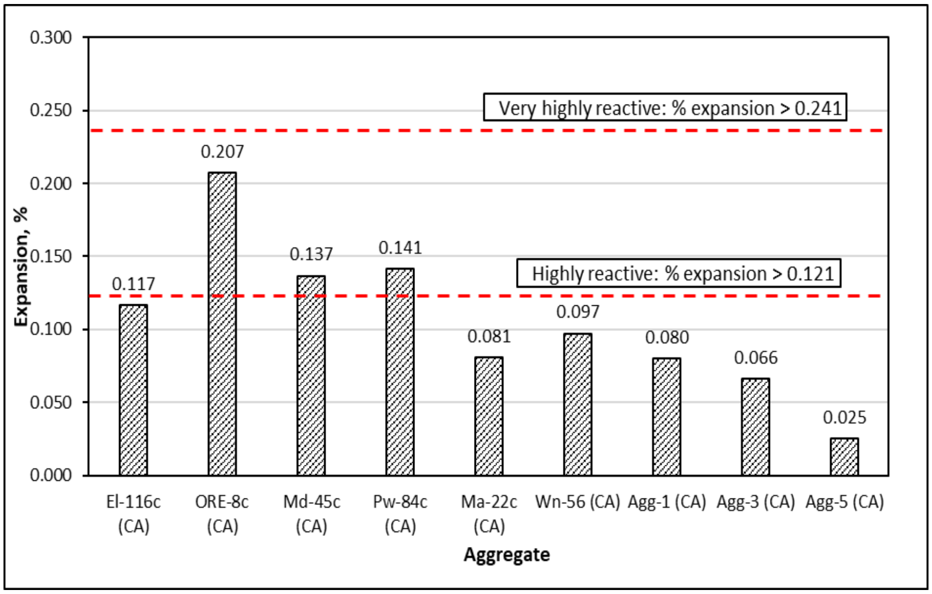


**Figure 18. 56-Day (MCPT) Expansion Values for Coarse Aggregate Fractions of the Materials Tested at the University of Idaho**

Likewise, results from testing the fine aggregate fractions showed expansion values greater than 0.04% for all the aggregate materials except Agg-5 (granite) (see Figure 19). Based on the results, all fine aggregates are considered reactive. In fact, most of the fine aggregate fractions fall under the 'very-highly reactive' category, with 56-day expansion values greater than 0.241%. The use of such aggregates in concrete can make it highly susceptible to ASR.

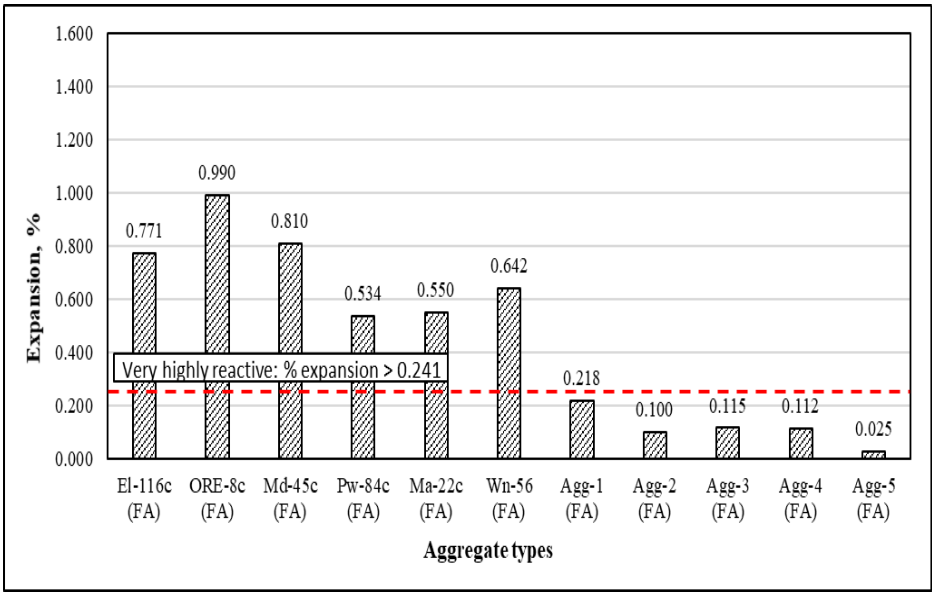


**Figure 19. 56-Day (MCPT) Expansion Values for Fine Aggregate Fractions of the Materials Tested at the University of Idaho**

## Percent Expansion of MCPT Specimen

Per AASHTO TP 110 specifications, change in specimen length was measured at Zero-day and periodically at 3, 7, 10, 14, 21, 28, 42, and 56 days after placement in the curing solution. Percent expansion values were calculated for each day, and have been plotted against the period of curing (see Figures 20 through 23). Figures 20 and 21 present the data for the coarse and fine aggregate fractions tested at Boise State University, whereas results from the testing at University of Idaho have been plotted in Figures 23 and 24. It can be observed from the figures that the rate of expansion of the concrete bars (indicated by the slope of the % Expansion vs. days curve), shows a generally increasing trend with age. From Figure 20, it can be seen that almost all the coarse aggregates except Wn-56 observed very little expansion up to 10 days. However, the rate of expansion increases significantly after that. The curves for different aggregate materials crossed the non-reactive (≤ 0.04 %) threshold at different ages. For example, the specimens for El-116c and Md-45c exceeded the 0.04% limit after only 14 days. On the other hand, the specimens for ORE 8c, Bg-111c, and Bn-155c crossed that limit in between 19 to 28 days. The curve for Ln-80c experienced an expansion of more than 0.04 % after 35 days. The expansion rate of the Wn-56 material was the highest among all, and the specimen expanded beyond the threshold limit of 0.04% in less than seven days. Another interesting behavior can be noted by looking at the plot corresponding to the Bn-155c material. This specimen exhibited little or no expansion till about 21 days, after which the rate of expansion increased drastically (as is evident from the sudden change in slope of the curve).

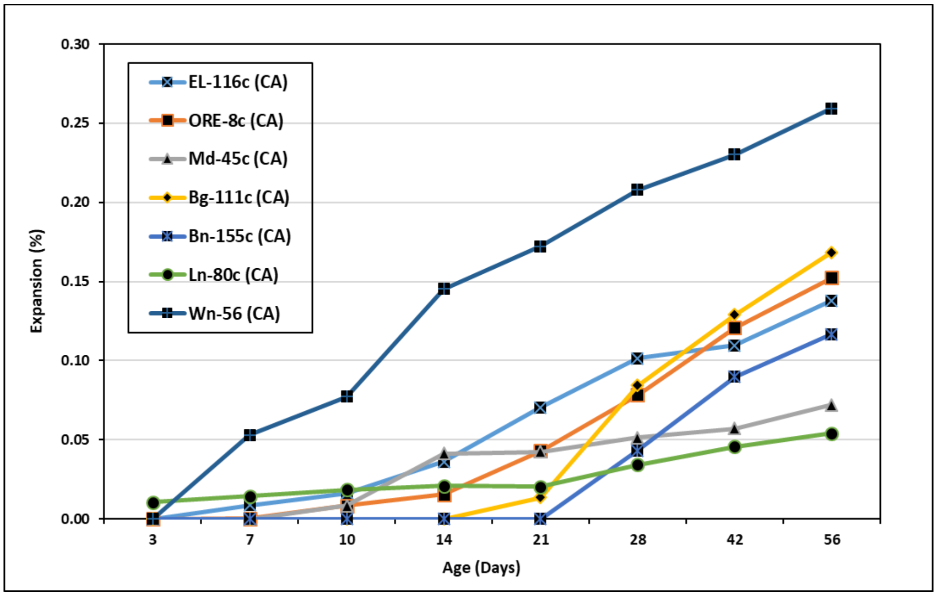


**Figure 20. Visual Representation of the Percent Expansion vs. Age Data for Coarse Aggregate Fractions Tested at Boise State University using MCPT**

Unlike coarse aggregate, the expansion of the fine aggregate samples was very high at an early age (Figure 21). Most of the aggregates, except Ln-80, exceeded the non-reactive criteria before seven-days period. Additionally, it was observed that the expansion of all the aggregate samples was proportional to age.

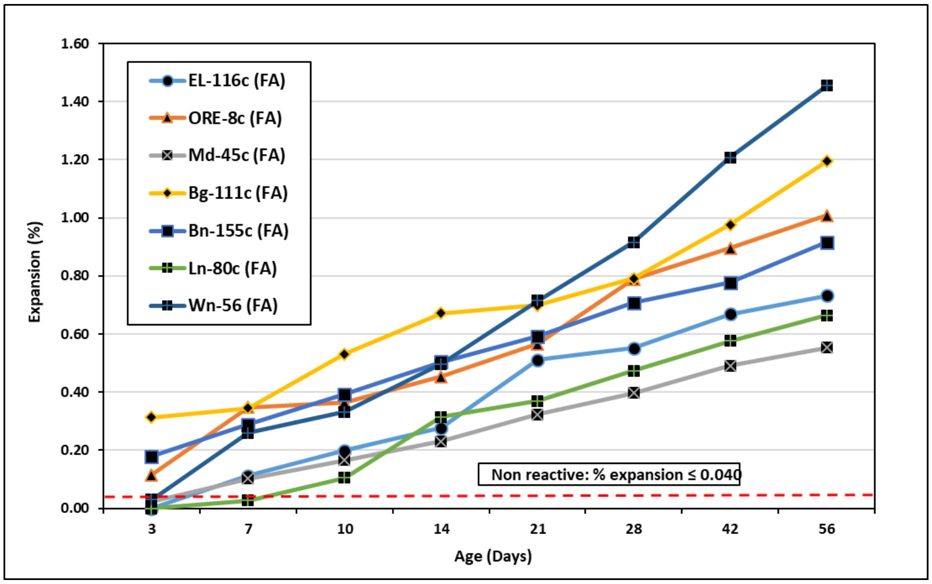


**Figure 21. Visual Representation of the Percent Expansion vs. Age Data for Fine Aggregate Fractions Tested at Boise State University using MCPT**

Figure 22 and Figure 23 show the percent expansion vs. age data for the coarse and fine aggregate fractions, respectively, for the materials tested at the University of Idaho laboratory. These results also confirm the prior observation regarding rate of expansion being proportional to curing age. Figure 22 shows that the rate of expansion can vary significantly from one aggregate material to another. For instance, one of the aggregate materials (e.g., ORE-8c) had a steeper slope compared to the rest. This particular aggregate (ORE-8c) was acquired from the western Snake River, and has a high silica content. Meanwhile, the expansion behavior of the coarse fraction of the reference material ( Agg-5) was linear across the age, with an expansion of 0.023% recorded at the 56-days. Similar trends were observed from the fine fraction testing at the University of Idaho (see Figure 23). The reference aggregate material (Agg-5; granite) exhibited the lowest reactivity, with the percent expansion remaining below the threshold value of 0.04% even after 56 days. Note that the fine fraction of ORE-8c exhibited the highest reactivity (percent expansion at 56 days = 0.99%); this was consistent with the level of reactivity observed for the coarse fraction of this material (see Figure 22).

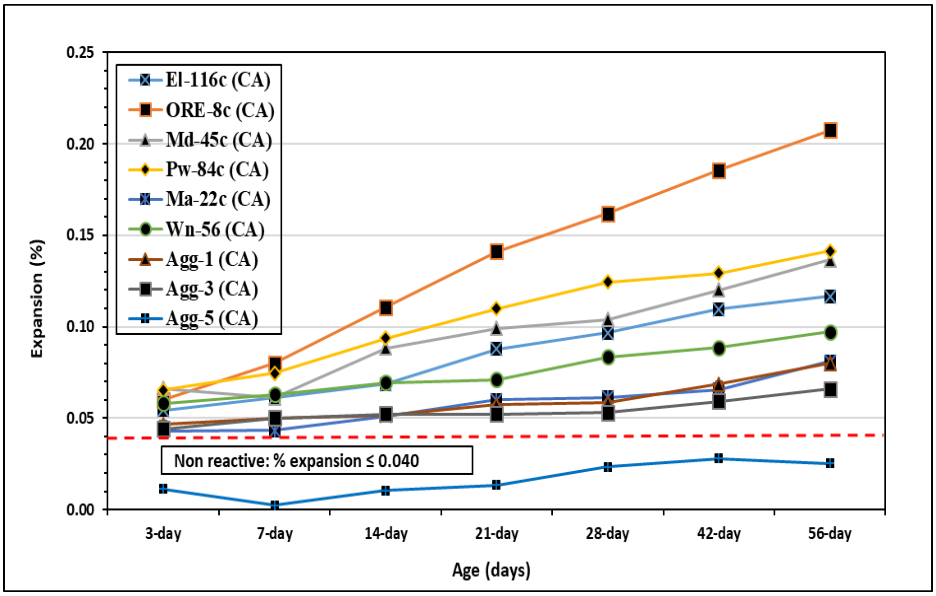


**Figure 22. Visual Representation of the Percent Expansion vs. Age Data for Coarse Aggregate Fractions Tested at the University of Idaho using MCPT**

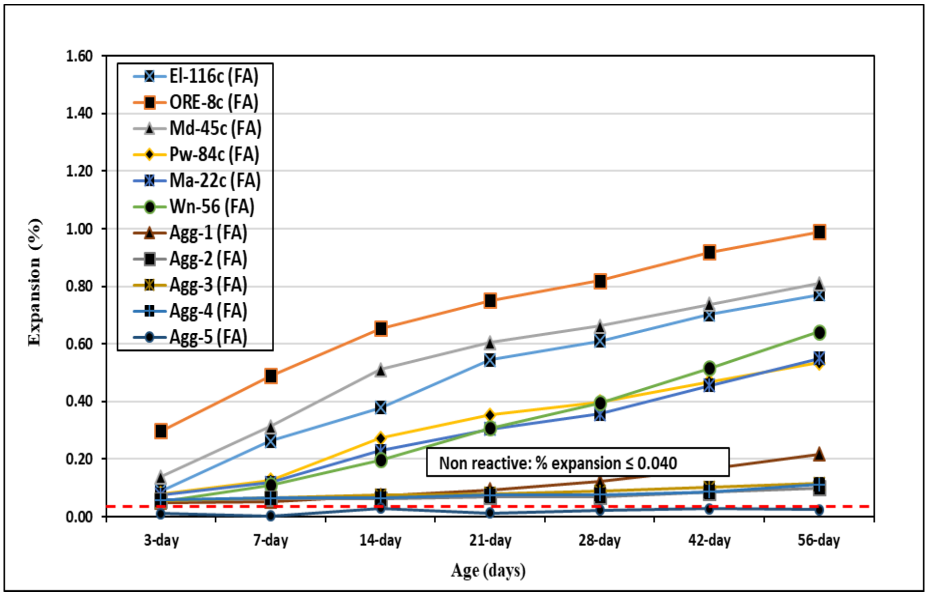


**Figure 23. Visual Representation of the Percent Expansion vs. Age Data for Fine Aggregate Fractions Tested at the University of Idaho using MCPT**

From the coarse and fine aggregate results discussed above, the following primary observations can be made: (1) All Idaho aggregates tested in this study using the 56-day MCPT were found to be ASR-susceptible; (2) the fine fractions of the aggregate materials exhibited significantly higher percent expansion values compared to the coarse aggregates. This can be attributed to the higher aggregate surface area available for the reaction to take place in case of the fine aggregates; (3) the coarse fractions of all the aggregate materials exhibited low expansion rates for the first 3-10 days. Subsequently, the reaction rates increased rapidly. On the other hand, for the fine fractions, high expansion rates were recorded from the very beginning of the test.

## Correlation Between Coarse Aggregate and Fine Aggregate MCPT Data

As the 56-day MCPT procedure requires the coarse and fine fractions of a particular aggregate material to be tested separately, the research team attempted to study whether the percent expansion trends were similar for the two size fractions or not. It should be noted that the primary difference between a CA or FA fraction being tested for ASR using MCPT is the aggregate surface area available for the reaction to take place. Accordingly, the percent expansion values observed for the two size fractions should show consistent trends. Results from the CA and FA fractions tested at the two university laboratories have been plotted together in Figure 24. Percent Expansion values for the CA fraction have been plotted along the X-axis, whereas the corresponding values for the fine fractions have been plotted along the Y-axis. Different points in the plot correspond to each aggregate material tested at the two laboratories. Note that the points represent the average (among all specimens for a particular aggregate material) percent expansion values established after 56 days. As seen from the figure, the percent expansion values for the FA fraction are consistently higher than those for the CA fraction. Nevertheless, a reasonable good correlation exists between the two data sets, as is established by a coefficient of determination ($R^2$) value of 0.74.

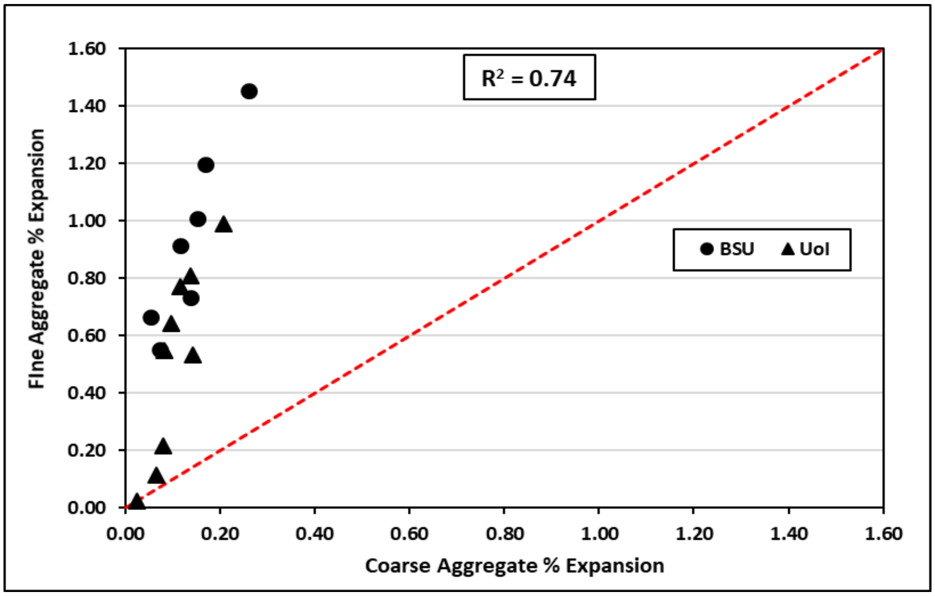


**Figure 24. Correlation Between 56 days Expansion Data for Coarse and Fine Aggregate Fractions Tested in the Current Study**

## Inter-Laboratory Variation in MCPT Results

As already mentioned, some of the aggregate materials used in the current study were tested at both the university laboratories. The objective was to assess the extent of inter-laboratory variability in the test results. This assessment is important to ITD and for future adoption of this test method into ITD specifications because tests are often conducted by different testing laboratories across the state in addition to the ITD central laboratories. Table 15 summarizes the 56-day MCPT results for the coarse and fine fractions of all overlapped aggregates (or aggregates tested at both university laboratories). The results showed that these aggregates were reactive at both laboratories. Meanwhile, as seen from the table, for two of the aggregate materials (e.g. EL-116c and ORE-8c), the results from the two laboratories were significantly close to each other. However, for the two other aggregate materials (Md-45c and Wn-56), significant differences in the results were observed. This could be due to some variations in specimen preparation or casting when testing these two materials.

**Table 15. Summary 56-Day MCPT Results for the Overlapped Aggregate Materials (materials that were tested at both the university laboratories)**

| Aggregate Name | % Expansion at 56 Days | | | |
|---|---|---|---|---|
| | Coarse Aggregate (CA) | | Fine Aggregate (CA) | |
| | BSU | UoI | BSU | UoI |
| El -116c | 0.138 | 0.117 | 0.732 | 0.771 |
| ORE-8c | 0.152 | 0.207 | 1.009 | 0.990 |
| Md-45c | 0.072 | 0.137 | 0.554 | 0.810 |
| Wn-56 | 0.259 | 0.097 | 1.454 | 0.642 |

Figure 25 compares the percent expansion values obtained from the two university laboratories for the “overlapped” aggregates. This figure shows that consistent results were obtained from the inter-laboratory testing, with the exception of one coarse aggregate type and two fine aggregate types.

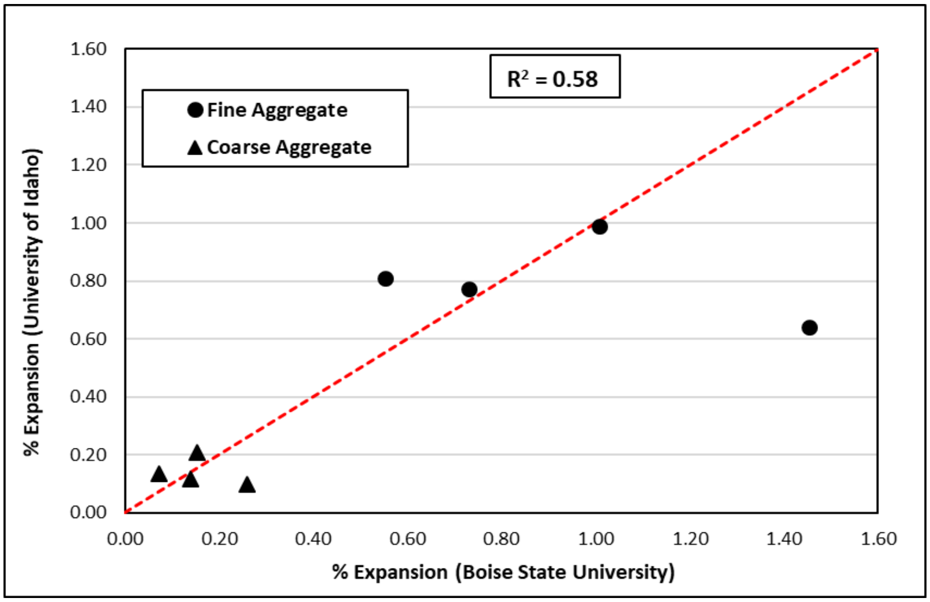


**Figure 25. Percent Expansion of Overlapped Aggregate Materials Established using the MCPT Method at the Two University Laboratories**

As already mentioned, the AASHTO TP 110 (now AASHTO T 380) method is relatively new. Therefore, the specification in its current version, does not include official precision and bias statements. Accordingly, the precision and bias calculations in the current study were carried out following the procedure specified by ASTM C1293 [8]. This particular standard was chosen as both the CPT and MCPT methods use a threshold expansion value of 0.04 % to differentiate between reactive and non-reactive aggregate materials.

The ASTM C1293 specification mentions that for average specimen expansion values greater than 0.02%, the within-laboratory Coefficient Of Variation (COV) of a multi-specimen test was found to be

12%. It also recommends that the difference between the highest and lowest expansion values of three test specimens should not be greater than 40% of the mean expansion value. Similar threshold values were adopted in the current study to check the within-laboratory and inter-laboratory variations in the MCPT results. Table 16 lists the within-laboratory precision values for the overlapped aggregate materials as calculated within the Boise State University and University of Idaho laboratories. The ratio of expansion difference to the mean expansion of the specimens was calculated, and compared against the threshold value of 40%. As seen from table 16, results for the coarse fraction of two of the aggregate materials (ORE-8c and Md-45c) tested at Boise State University did not meet the specified threshold value. However, results for the same material from University of Idaho were well below the threshold value of 40%. Therefore, it is recommended that these two data points should be excluded from the Boise State test results. Note that testing additional replicates of these aggregates was not possible under the scope of this study due to unavailability of sufficient aggregate materials.

**Table 16. Within-Laboratory Precision of MCPT Results of Overlapped Aggregate Materials Tested at Boise State University and University of Idaho Laboratories**

| Laboratory | Agg. Name | Agg. Fraction | Mean Expansion (%) | Highest Expansion (%) | Lowest Expansion (%) | Expansion Difference | Ratio of Expansion Difference to Mean (%) | Check if Ratio ≤ 40% or not |
|---|---|---|---|---|---|---|---|---|
| Boise State University | El -116c | CA | 0.138 | 0.161 | 0.120 | 0.041 | 29.71 | ok |
| | | FA | 0.732 | 0.789 | 0.657 | 0.132 | 18.04 | ok |
| | ORE-8c | CA | 0.152 | 0.209 | 0.092 | 0.117 | 76.97 | not ok |
| | | FA | 1.009 | 1.033 | 0.978 | 0.055 | 5.45 | ok |
| | Md-45c | CA | 0.072 | 0.116 | 0.003 | 0.113 | 156.94 | not ok |
| | | FA | 0.554 | 0.587 | 0.530 | 0.057 | 10.30 | ok |
| | Wn-56 | CA | 0.259 | 0.269 | 0.253 | 0.016 | 6.17 | ok |
| | | FA | 1.454 | 1.478 | 1.420 | 0.058 | 3.99 | ok |
| University of Idaho | El -116c | CA | 0.117 | 0.127 | 0.109 | 0.018 | 15.43 | ok |
| | | FA | 0.771 | 0.796 | 0.757 | 0.039 | 5.06 | ok |
| | ORE-8c | CA | 0.207 | 0.215 | 0.201 | 0.014 | 6.75 | ok |
| | | FA | 0.990 | 1.013 | 0.960 | 0.053 | 5.36 | ok |
| | Md-45c | CA | 0.137 | 0.147 | 0.125 | 0.022 | 16.10 | ok |
| | | FA | 0.810 | 0.835 | 0.781 | 0.054 | 6.67 | ok |
| | Wn-56 | CA | 0.097 | 0.105 | 0.090 | 0.015 | 15.70 | ok |
| | | FA | 0.642 | 0.659 | 0.625 | 0.034 | 5.30 | ok |

The multi-laboratory precision values were also evaluated following this procedure specified in ASTM C1293 standard. Per ASTM C1293, for average specimen expansion values greater than 0.014 %, the difference between the two laboratory's test results for an identical material should be less than 65% of the mean of the two results. Table 17 summarizes the multi-laboratory variations for the MCPT results between the two laboratories using the overlapped aggregate materials. As seen from the table, the threshold value of 65% was exceeded for only one aggregate material (Wn-56; both for coarse as well as fine fractions). Once again, repeated testing was not available due to lack of material availability.

**Table 17. Multilaboratory Variations of the of MCPT Results for Overlapped Aggregate Materials Tested at the Two University Laboratories**

| Aggregate Name | Aggregate Type | Results (%) | | Mean of Results (%) | Results Difference | Ratio of Results Difference to Mean (%) | Check if Ratio < 65 % or not |
|---|---|---|---|---|---|---|---|
| | | BSU | UoI | | | | |
| El -116c | CA | 0.138 | 0.117 | 0.128 | 0.021 | 16.47 | ok |
| | FA | 0.732 | 0.771 | 0.752 | 0.039 | 5.19 | ok |
| ORE-8c | CA | 0.152 | 0.207 | 0.180 | 0.055 | 30.64 | ok |
| | FA | 1.009 | 0.990 | 1.000 | 0.019 | 1.90 | ok |
| Md-45c | CA | 0.072 | 0.137 | 0.105 | 0.065 | 62.20 | ok |
| | FA | 0.554 | 0.810 | 0.682 | 0.256 | 37.54 | ok |
| Wn-56 | CA | 0.259 | 0.097 | 0.178 | 0.162 | 91.01 | not ok |
| | FA | 1.454 | 0.642 | 1.048 | 0.812 | 77.48 | not ok |

Comparing the individual percent expansion values listed for the aggregates (both coarse and fine fractions) from the two universities, it can be seen that no particular trend is observed in terms of results from one particular university being greater or lower in magnitude than those from the other. Some of the aggregates materials recorded higher percent expansion values at Boise State University, whereas, the others recorded higher values at University of Idaho. This clearly eliminates the possibility of the testing conditions at one laboratory being consistently “harsher” or “milder” than the other. Differences in the test results can be attributed to random variabilities introduced into the test method during processes such as material fractionation, sample preparation, etc.

## 14-day AMBT Results

As already mentioned, one of the objectives of the current research effort was to compare results from the 56-day MCPT with other commonly used tests such as the 14-day AMBT and the 1-year CPT. All the aggregate materials collected from the ITD RP 212 material archives already had associated 14-day AMBT results available. Nevertheless, the research team decided to run additional AMBT tests on some of the aggregate materials. Note that most of the AMBTs in the current study were performed at the University of Idaho laboratory. The fine fractions of eleven (11) aggregate materials (obtained after crushing the coarse aggregate fractions to a required size distribution) were tested using the 14-day AMBT method as per ASTM C1260, and the results have been presented in Table 19. According to ASTM C1260 and AASHTO T 303, an aggregate material is designated as being ASR-susceptible when the average expansion of AMBT bars at 14 days crosses 0.10% limit. It can be clearly observed from Table 19 that most of the aggregate materials tested in this current study were found to be reactive with a few exceptions, which are non-reactive (i.e., Agg-2, Agg-3, and Agg-5).

**Table 18. Summary of 14 Days AMBT Results**

| Aggregate Types | % Expansion at 14-days | Check Reactivity |
|---|---|---|
| EI-116c | 0.594 | Reactive |
| ORE-8c | 0.754 | Reactive |
| Md-45c | 0.535 | Reactive |
| Ma-22c | 0.312 | Reactive |
| Pw-84c | 0.403 | Reactive |
| Wn-56 | 0.518 | Reactive |
| Agg-1 | 0.375 | Reactive |
| Agg-2 | 0.070 | Non – Reactive |
| Agg-3 | 0.049 | Non- Reactive |
| Agg-4 | 0.223 | Reactive |
| Agg-5 | 0.009 | Non-Reactive |

## Correlation between MCPT and AMBT

Once all the 56-day MCPT and 14-day AMBT results were compiled, the next step was to compare the reactivity levels for individual aggregate materials established by these two test methods. As already discussed, the 14-day AMBT test has been criticized in the past for its aggressive test conditions and frequent false positive (and occasional false negative) values. Comparing the percent expansion values established by the two test methods would give an idea regarding the adequacy of the MCPT as a potential replacement to the AMBT.

The correlation between the 56-days MCPT method (fine fraction) and 14-day AMBT test results for 11 aggregate samples with different reactivity levels tested at the University of Idaho is shown in Figure 26. The results showed that there is a strong relationship between the two test procedures with an $R^2$ value of 0.88. Note that Figure 26 as well as some of the subsequent figures have red straight lines (vertical and horizontal) drawn to delineate the boundaries between non-reactive and reactive materials as defined by the two test methods. One thing to notice from Figure 26 is that the expansion values recorded by the MCPT method (fine fraction) were consistently higher than those established from the 14-day AMBT method, which is not in agreement with the results reported by Latifee and Rangaraju [7]. From their testing, the percent expansion values from AMBT were consistently higher than those from MCPT. Such a trend would generally be expected as the AMBT subjects the specimens to significantly “harsher” curing conditions. However, test results from the current study (from both university laboratories) demonstrated trends where the percent expansion values from MCPT were higher than those from AMBT. No particular justification for this trend could be established.

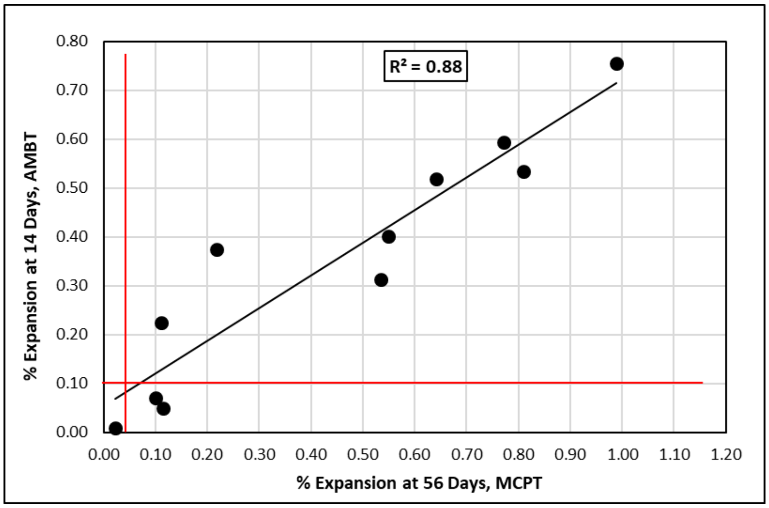
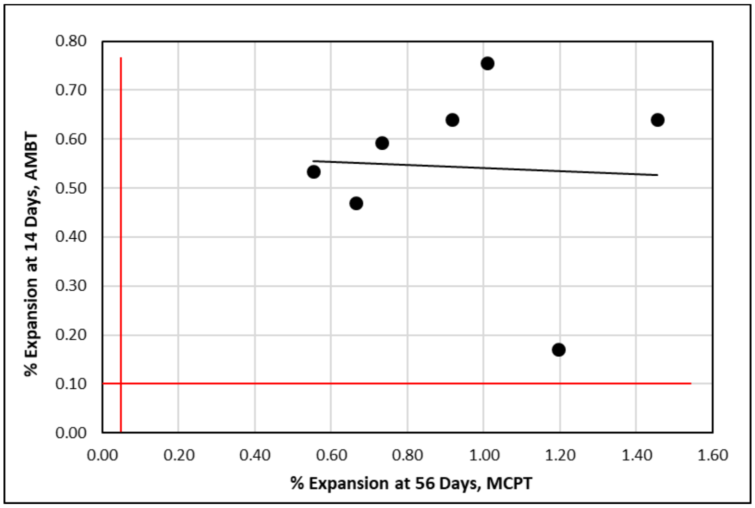
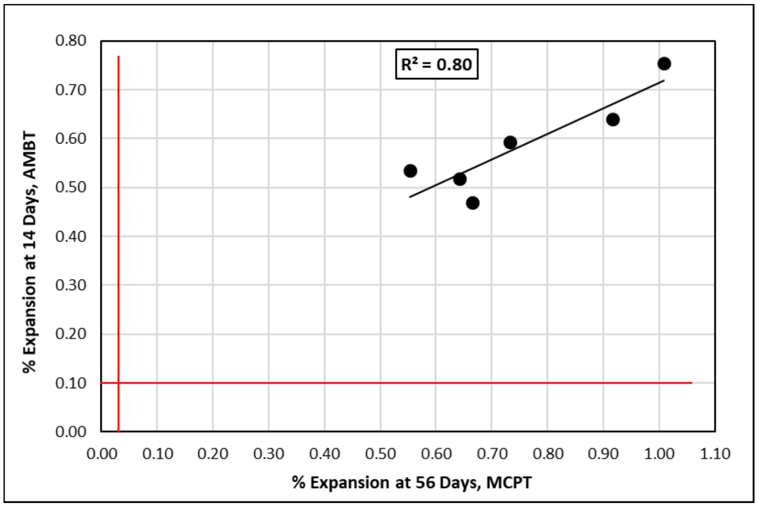


**Figure 26: Correlation between 56-day MCPT (fine fraction) and 14-days AMBT Data (Tests Conducted at University of Idaho)**

Figure 27a shows the correlation between 56-day MCPT and 14-day AMBT test results for the aggregate materials tested at Boise State University. Note that the AMBT results were extracted from the database generated by Gillerman and Weppner[28]. As seen from the figure, a very weak correlation was initially observed between the percent expansion values obtained from the two methods. A careful review of the test results revealed that this poor correlation was primarily because of two aggregate types (Bg-111c and Wn-56) that resulted in significantly different percent expansion values when tested by the two methods. The 56-day MCPT expansion values for the two aggregates were 1.20% and 1.45%, respectively, whereas the corresponding values from the 14-day AMBT were 0.17% and 0.64%. Not only are the percent expansion values from the two methods significantly different, the percent expansion values from MCPT are significantly greater than those from the AMBT, which is opposite to the trends reported by Latifee and Rangaraju [7]. Figure 27 (b) was prepared by removing the Bg-111c data and replacing the MCPT value for Wn-56 by that determined at University of Idaho. This led to a much better correlation, with $R^2$ = 0.80, which indicates a perfect correlation between the test methods.



**(a)**



**(b)**

**Figure 27: Correlation between 56-days MCPT (tested at BSU) and 14-days AMBT Data; (a) Considered all the Tested Aggregate Samples; (b) Truncated Bg-111c and Wn-56 materials.**

Figure 28 evaluates the correlation between the MCPT and AMBT test results considering all the aggregate materials (except Bg-111c) tested in the two laboratories. While preparing this plot, data for the overlapped aggregates from each laboratory have been treated as independent test results. Excellent overall correlation was observed between the two test methods ($R^2 = 0.90$). Overall, most of the test aggregates were reactive using both test methods. Nevertheless, the major discrepancy in the trends compared to those reported by Latifee and Rangaraju [7] remains with the fact that the percent expansion values from MCPT were consistently higher than those from AMBT.

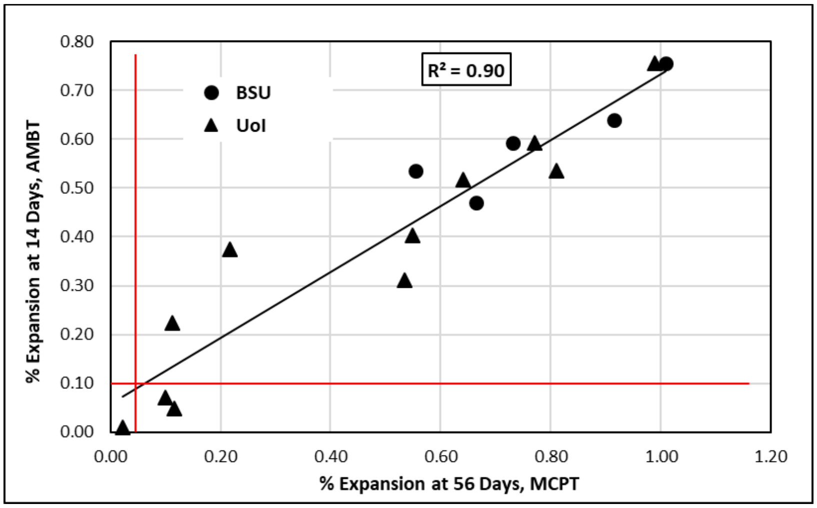


**Figure 28: Correlation between 56-days MCPT (combined results) and 14-days AMBT Data**

A total of 34 MCPT tests were performed on coarse and fine fractions of 14 different aggregate materials at the two university laboratories. As mentioned earlier, 4 aggregate materials were tested at both laboratories to assess inter-laboratory variations in the test results. Not all aggregate materials could be tested using the AMBT method under the scope of this project due to lack of material availability. Therefore, the 14-day AMBT expansion data of some of the aggregate materials (Bg-111c, Bn-155c, and Ln-80c) were extracted from the database generated by Gillerman and Weppner [28].

Figure 29 compares the percent expansion values for all aggregate materials (coarse and fine fractions) determined from the 14-day AMBT and 56-day MCPT methods. It can be clearly seen from the figure that the percent expansion values determined from MCPT for the aggregate fine fractions were consistently higher than the corresponding 14-day AMBT results for the same materials. Here it should be noted that 14-day AMBT test is a mortar bar test, and therefore, all aggregates are crushed to smaller than 4.75 mm. Accordingly, AMBT results cannot be divided into "coarse" and "fine" fractions, unlike the CPT and MCPT. As seen from Figure 29, the percent expansion values for the fine fractions determined from MCPT were greater than those from AMBT. On the other hand, the expansion percentages recorded from MCPT on the coarse fractions were consistently lower than the AMBT values for those aggregates.

The higher reactivity of the fine fractions from MCPT were not consistent with the findings by Latifee and Rangaraju [7]. By testing 12 reactive and non-reactive aggregate materials (both coarse and fine fractions), they observed that percent expansion values from MCPT were lower than AMBT for both coarse and fine fractions. The AMBT method subjects the test specimens to significantly "harsher" conditions compared to the MCPT. It would generally be expected that AMBT specimens would expand more compared to MCPT specimens. However, the fine fractions of aggregate materials tested in the current study deviated from that trend. The research team could not identify certain reasons behind this inconsistent trend.

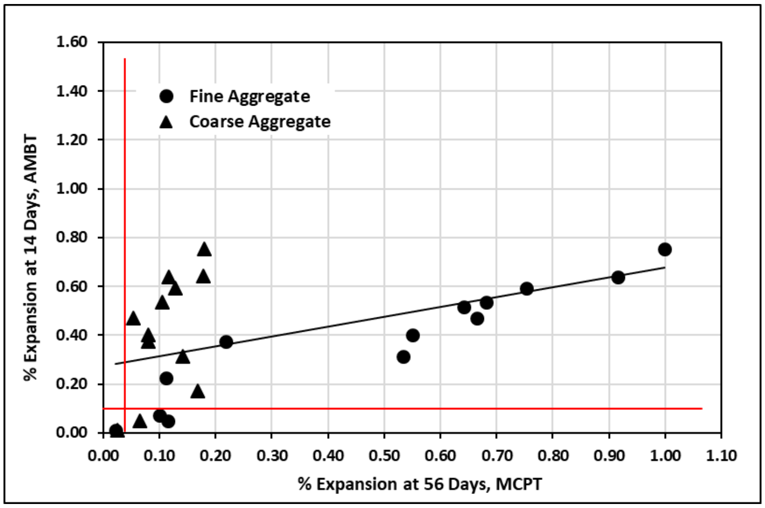


Figure 29. Comparison between of 56-Days MCPT Expansion Data and 14-days AMBT Expansion Data

## Comparing 14-Day AMBT Results with those Reported by Gillerman and Weppner (ITD RP 212)

Not all the aggregate materials collected from the RP 212 archives had sufficient quantities to be tested using MCPT as well as AMBT. Therefore, the 14-day AMBT tests were conducted on only those aggregate materials, for which sufficient aggregate quantities were available. For those materials that could be tested using the 14-day AMBT method, the research team compared the results obtained from the current study with those reported by Gillerman and Weppner [28]. Such a comparison would facilitate verification of the test results from the current study. Table 19 lists the 14-day AMBT expansion percentages for five different aggregate materials that were tested by Gillerman and Weppner [28] as well as the current study. As seen from the table, the results show a very close match for four of the five aggregate materials (only the results for Pw-84c from the two studies did not match). The research team could not ascertain the exact reason for the discrepancy in results for this particular material. Nevertheless, as four out of five results showed excellent match, the 14-day AMBT results from the current study can be said to have been validated.

Table 19. Comparison of 14 Days AMBT Results of RP 271 and RP 212

| Aggregate Name | % Expansion at 14-days, AMBT | |
|---|---|---|
| | RP 271 (current study) | RP 212 |
| El-116c | 0.593 | 0.570 |
| ORE-8c | 0.755 | 0.680 |
| Md-45c | 0.535 | 0.540 |
| Ma-22c | 0.312 | 0.330 |
| Pw-84c | 0.402 | 0.860 |

## 1-Year CPT Results

As explained in Chapter 3, the current study included additional testing of six of the aggregate materials using the 1-year CPT and the 6-month ACPT methods. These additional tests were conducted at the University of Idaho laboratory. The temperature and duration for conditioning the test specimens are different in both test methods (i.e., 1-year CPT and 6-month ACPT). The conditioning temperature for the 1-year CPT was 38ºC (100°F), while it was 60ºC (140°F)for the 6-month ACPT methods [40]. Table 20 summarizes both test results. For the 6-month ACPT results, all six aggregates exceeded the 0.04% ASR threshold for non-reactive aggregates, excluding Agg-5 (granite rock) (0.03% expansion). The Agg-5 (granite rock) was found non-reactive, which is in good agreement with the results obtained from both the 56-days MCPT and 14-days AMBT. The Wn-56 aggregate material had the highest expansion rate of 0.1% after six months, as shown in Figure 30. Similarly, the expansion results for the 1-year CPT follow that of 6-month ACPT results. However, the results of CPT of four out of the six test aggregate materials, were found to be slightly higher compared to the ACPT expansion results. Meanwhile, there was excellent correlation ($R^2$ = 0.94) between the results of both test methods (Figure 31).

**Table 20. Summary of 1-year CPT and 6-months ACPT Results**

| Aggregate Name | % Expansion | | Check Reactivity | |
|---|---|---|---|---|
| | 1-year CPT | 6- Months ACPT | 1-year CPT | 6- Months ACPT |
| Wn-56 | 0.115 | 0.101 | Reactive | Reactive |
| Agg-1 | 0.071 | 0.084 | Reactive | Reactive |
| *Agg-2* | 0.056 | 0.066 | Reactive | Reactive |
| *Agg-3* | 0.049 | 0.042 | Reactive | Reactive |
| *Agg-5* | 0.029 | 0.024 | Non-Reactive | Non-Reactive |
| *Agg-4* | 0.087 | 0.072 | Reactive | Reactive |

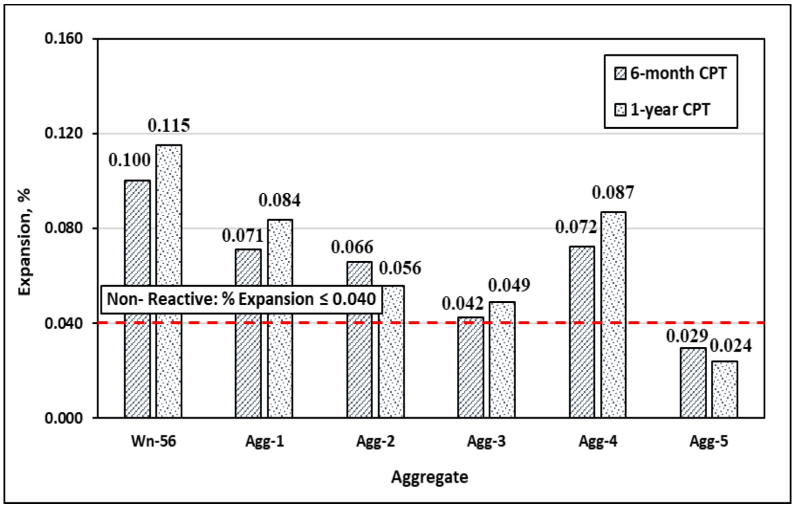


**Figure 30. Comparison between 1-year CPT Expansion Data and 6-months ACPT Expansion Data**

Figure 31 shows a comparison between the expansion of the CPT specimens after 1-year and expansion of the ACPT specimens 6-month current study. As mentioned earlier, it can also be seen from the figure that for most of the aggregate materials a slightly higher expansion was recorded for 1-year CPT bars than the 6-months ACPT bars. Both test methods have a good correlation with R squared value of 0.94.

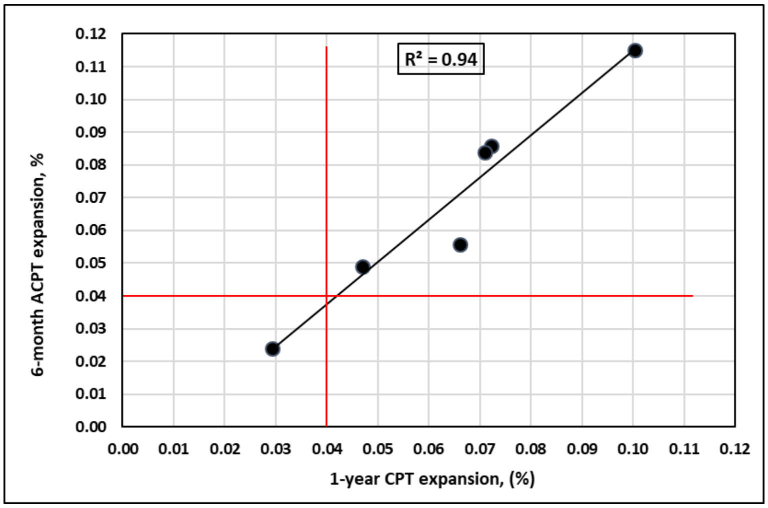


**Figure 31: Comparison between 1-year CPT Expansion Data and 6-months ACPT Expansion Data**

As discussed earlier, although all the aggregate samples were tested with the MCPT method, only a few of them (listed in Table 20) were tested using the 1-year CPT method. Note that due to the lack of available aggregate materials, the 1-CPT testing was run on the fine fractions only. So the comparison between the expansion data of MCPT and CPT tests was established based on the fine aggregates results only. Figure 32 shows the correlation between the 56-days MCPT and the 1-year CPT test results. As seen from figure 32, the 56-days MCPT and 1-year CPT test results have a good correlation ($R^2$ = 0.72). However, even in Figure 32, the percent expansion reported by the 56-day MCPT method were higher than those from the 1-year CPT method. This is inconsistent with the expansion trends observed by the researchers [7] during the original development of the MCPT method.

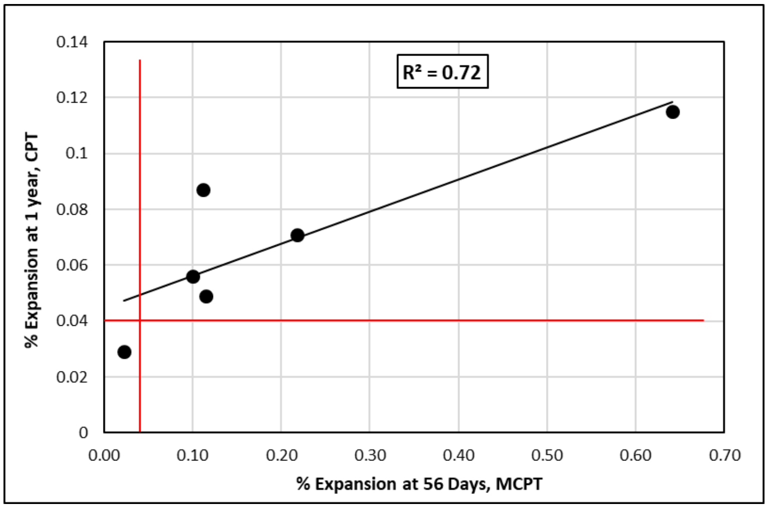


**Figure 32: Comparison between 56-days MCPT Expansion Data and 1-year CPT Expansion Data**

Figure 33 shows the correlation between MCPT and ACPT data. A fair correlation between both MCPT and ACPT (R-squared value (0.62) was obtained. It should be noted that the ACPT takes half of the time as the CPT method. Accordingly, once widely accepted, this method may be a better alternative to the 1-year CPT (Figure 31 clearly showed excellent correlation between the 6-month ACPT and the 1-year CPT results).

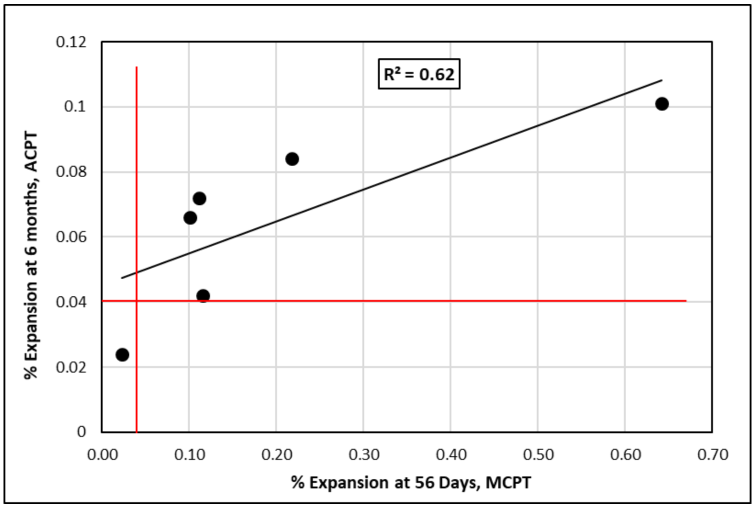


**Figure 33. Comparison between 56-days MCPT Expansion Data and 6-months ACPT Expansion Data**

## False-Positive or False-Negative Aggregates

As discussed in the earlier sections, this research project has tested fourteen (14) different fine aggregate samples using the MCPT method, and most of them were also tested using the AMBT method. The AMBT data of the aggregate samples that were not tested for AMBT were collected from Gillerman and Weppner[28]. Test results indicated that all the aggregate samples that were designated as being reactive using the MCPT method, were also found to be reactive using the AMBT method. This eliminated the possibility of false-positive or false-negative results. It should also be noted that to get an accurate idea of the false-positive and false-negative results, the laboratory test results should be compared to field performance of the aggregates as far as ASR-susceptibility is concerned. In the absence of field data, it may be premature to comment on whether or not the 56-day MCPT method is likely to give false-positive and/or false-negative results.

# Chapter 5
# Summary, Conclusions, and Recommendations

## Summary

Alkali-Silica Reaction (ASR) is a widely known reaction between the silica ($SiO_2$) content of aggregate and alkali content (sodium, $Na^+$, and potassium, $K^+$) of cement in the presence of available moisture. It is one of the most harmful concrete reactions, which can cause partial or complete damage to concrete structures. One of the main concerns of this damaging reaction is the difficulty of stopping the reaction once it starts inside a concrete structure. This research effort primarily focused on evaluating the suitability of a newly developed test method (AASHTO TP 110: Miniature Concrete Prism Test; MCPT) into practice in the state of Idaho to evaluate the ASR-susceptibility of concrete aggregates. The newly developed 56-days Miniature Concrete Prism Test (MCPT) was successfully evaluated for the first time in Idaho through this research project. At the time of initiation of this project, the MCPT method was designated as AASHTO TP-110. Later in 2019, it was adopted by AASHTO as AASHTO T 380-19. However, as all testing under the scope of this study were carried out per the AASHTO TP-110 method, the findings should not be blindly extended to AASHTO T-380 (the research team has not yet carefully compared the AASHTO TP-110 and AASHTO T-380 specifications).

A total of 14 different aggregate materials (both coarse and fine fractions), including one non-reactive reference aggregate, were collected from various sources across and close to Idaho, and were tested using the 56-days MCPT method. Most of the selected aggregates were also tested using the 14-day Accelerated Mortar Bar Test (AMBT) method (ASTM C1260 or AASHTO T 303). Additionally, the fine fractions of six of the aggregate materials were also tested using the 1-year Concrete Prism Test (CPT; ASTM C1293) and 6-month Accelerated Concrete Prism Test (ACPT). Table 21 summarizes the ASR-susceptibility levels of all the aggregate materials tested in the current study using the different test methods. Based on the testing conditions that specimens are subjected to, it can be hypothesized that the 56-day MCPT would be more reliable in assessing the ASR susceptibility of aggregates compared to the harsher 14-day AMBT method.

## Conclusions

The following conclusions can be drawn from findings of this research study:

1. All aggregate materials tested using different test methods under the scope of the current study were identified as being ASR-susceptible with various (mostly high) reactivity levels. Only the aggregate material used as the reference aggregate was confirmed to be non-reactive using all methods.
2. Per the reactivity criteria specified in AASHTO TP-110, the fine fractions of most of the aggregate materials tested in the current study were designated as “Very Highly Reactive”. On the other hand,

the reactivity levels of the coarse fractions varied between "Moderately Reactive" to the "Very Highly Reactive" categories.

**Table 21. Summary ASR Reactivity of Idaho Aggregate**

| Aggregate Name | Coarse Aggregate (CA) Reactivity | Fine Aggregate (FA) Reactivity | | | |
|---|---|---|---|---|---|
| | MCPT (56-days) | MCPT (56-days) | AMBT (14-days) | CPT (1-year) | ACPT (6-month) |
| EI-116c | Highly Reactive | Very Highly Reactive | Very Highly Reactive | NA | NA |
| ORE-8c | Highly Reactive | Very Highly Reactive | Very Highly Reactive | NA | NA |
| Md-45c | Moderately Reactive | Very Highly Reactive | Very Highly Reactive | NA | NA |
| Ln-80c | Highly Reactive | Very Highly Reactive | NA | NA | NA |
| Bg-111c | Moderately Reactive | Very Highly Reactive | NA | NA | NA |
| Bn-155c | Moderately Reactive | Very Highly Reactive | NA | NA | NA |
| Pw -84c | Highly Reactive | Very Highly Reactive | Highly Reactive | NA | NA |
| Ma-22c | Moderately Reactive | Very Highly Reactive | Highly Reactive | NA | NA |
| Wn-56 | Very Highly Reactive | Very Highly Reactive | Very Highly Reactive | Moderately Reactive | Moderately Reactive |
| Agg-1 | Moderately Reactive | Highly Reactive | Highly Reactive | Moderately Reactive | Moderately Reactive |
| Agg-2 | NA | Moderately Reactive | Non-Reactive | Moderately Reactive | Moderately Reactive |
| Agg-3 | Moderately Reactive | Moderately Reactive | Non-Reactive | Moderately Reactive | Moderately Reactive |
| Agg-4 | NA | Moderately Reactive | Moderately Reactive | Moderately Reactive | Moderately Reactive |
| Agg-5 | Non-Reactive | Non-Reactive | Non-Reactive | Non-Reactive | Non-Reactive |

3. The within-laboratory and multi-laboratory variations for the MCPT test results were determined based on the precision limits recommended by the ASTM C1293 (CPT) standard. The analysis revealed that both within-laboratory and multi-laboratory variations were generally within the specified limits, with a few exceptions. As more test data becomes available, AASHTO will include official precision and bias statements to the specification.
4. From the results it was observed that the 56-day MCPT method reported greater percent expansion values for aggregate fine fractions compared to results from the 14-day AMBT as well as 1-year CPT

methods. This was an unexpected trend as AMBT testing is a “harsher” test that subjects the test specimens to higher temperatures compared to the MCPT. Unlike the results for the fine fractions, the MCPT specimens for the coarse aggregate fractions generally showed lower expansion percentages compared to AMBT specimens. Due to the lack of material availability, the 1-year CPT test was not performed on the coarse aggregate fractions in this study. Therefore, no comparison was made between the expansion percentages for the 56-day MCPT and 1-year CPT methods for the coarse aggregate fractions.

## Recommendations for Future Research

Although the current study achieved its primary objective of evaluating the ASR-susceptibility of different Idaho aggregates using the newly developed MCPT method, more testing and verification efforts are required before this method can be officially incorporated into ITD specifications. The following recommendations are provided for ITD to move towards more extensive evaluation and subsequent implementation of this test method into standard practice.

1. All aggregate materials tested in the current study were found to be reactive as far as ASR-susceptibility is concerned. This prevented the research team from assessing the suitability of this test method for identifying non-reactive aggregates. Future studies should carefully select aggregates to ensure similar number of non-reactive, moderately reactive, and highly-reactive sources are tested.
2. The current study primarily compared the MCPT results with those from AMBT and CPT methods. However, as it is widely known, true indication of the ASR susceptibility of different aggregate materials can only be obtained from field performance assessment. ITD should therefore undertake carefully planned initiatives to monitor the field performance of some of the aggregates tested in this study. That would facilitate the comparison of the laboratory findings with field performance.
3. The current study involved testing of only a limited number of aggregates using the 1-year CPT method; moreover, only the fine fractions of these aggregates were tested. As the 1-year CPT method has been widely accepted to correlate well with field performance, it is recommended that future studies be structured in a manner that would facilitate extensive testing of both coarse and fine fractions of several aggregates using the 56-day MCPT as well as the 1-year CPT methods. This can be facilitated by extensive coordination, data sharing, and consistent testing by research laboratories, ITD’s central laboratory, as well as different material testing laboratories within the state of Idaho.
4. The current study did not include the evaluation of any mitigation strategies. Once the reliability of this test method has been thoroughly investigated (through testing efforts undertaken by multiple research teams and/or state agencies), future research efforts can focus on evaluating different ASR-mitigation strategies. Once proved to be a reliable method, the MCPT can be used instead of the 1-year CPT to test the effectiveness of ASR mitigation approaches utilizing Secondary Cementitious Materials (SCMs).

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# Appendix A
# Summary of Test Methods Available to Determine ASR

## Summary of Previously Developed ASR Test Methods

Latifee (2013) [40] summarized 23 available ASR test methods in his doctoral dissertation which have been presented in this section.

### *Stanton, T.E., 1940, California Division of Highway*

In the late 1930s, Thomas E. Stanton of the California Division of Highway first identified the ASR (Stanton 1940). His research into ASR reaction and test methods to evaluate the potential of aggregates to undergo ASR started in May 1938 and continued for five years. His research into a test method examined several different specimen geometries and proportions including mortar bars (1 in. x 1 in. x 10 in.), concrete prisms (2 in. x 2 in. x 11.25 in. with 50% sand and 50% coarse aggregate, max. aggregate size of 0.75 inches), mortar cylinders (2 in. dia. x 4 in. long) which were subjected to different curing conditions. These included continual wetting, continual drying, normal laboratory temperature and humidity, and alternate wetting and drying. The curing methods used were sealed container, air and water. The test duration varied from twenty-eight days to five years. The test specimen conditioning temperature ranged from 70°F to 150°F (21.1°C - 65.5°C), and in some cases cycling heating and cooling. He found that certain mineral constituents in some aggregates such as certain types of shales, cherts, and impure limestones found along the coast of California between Monterey Bay on the north and Los Angeles county on the south, had the potential to cause deleterious expansion in concrete due to some chemical reaction and it only happened when cement contained appreciable percentage of alkali as sodium and potassium oxides. If the alkali content of cement was less than 0.6% then the expansion observed was found to be negligible. Another conclusion was that the partial replacement of high-alkali cement with a suitable pozzolanic material prevented excessive expansions. His work formed the basis for the ASTM C227 standard test method (mortar-bar test procedure).

### *ASTM C227-10, 1950, Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)*

This test method was first published in 1950 and is based on the testing methodology described by Stanton (1940). ASTM C227 was last reapproved/revised in2010. The test involves molding mortar bars (1 in. x 1 in. x 11.25 in) containing either the fine aggregate or the coarse aggregate (which has been crushed and graded to sizes required by ASTM C227) in question and either a job cement or a reference cement of known alkali level. Some aggregates such as gneisses and greywacke, which are more slowly reacting, will only expand in the mortar-bar test if the alkali content of the cement is boosted by the addition of alkali to a level of 1.25 percent. The mortar is placed in metal molds to fabricate a set of four mortar bars. After hardening, i.e., keeping in the moist cabinet or room for 24 hours, the four mortar bars are demolded and measured for initial length. The specimens are placed over water in containers, and the containers are sealed to maintain 100 percent relative humidity. It is kept for 12 days at 38°C (100°F) and then at 23°C

(73°F) and after 14 days the length is measured. Additional information of value may often be obtained by returning the specimens to the 38.0°C (100°F) storage after the 14- day test and making additional measurements at later ages of 1, 2, 3, 4, 6, 9, and 12 months. An average length change (for the four mortar bars) greater than 0.05 percent at three months and greater than 0.10 percent at six months test age is considered by ASTM C 33 to be excessive and indicative of potentially deleterious ASR.

The problem of alkali leaching in this test was first reported before the test became standardized [Blanks et al., 1946] and the failure of test to correctly identify the potential reactivity of a numerous rock types is now well established [ACI 201-2R-0521; ACI 221-1R-98; Rogers et al., 2000; Rogers et al., 1989]. Another problem is maintaining optimum moisture conditions in the storage containers. For this reason, mortar bars made with greywacke, gneiss or other slower reacting aggregates are recommended to be stored in containers over water but without wicks [Rogers et al., 1989]. It is reported that insignificant expansion of mortar bars may result when potentially deleteriously reactive siliceous rocks are present in comparatively high proportion even when high-alkali cement is used in this test. This may occur because the alkali-silica reaction products are characterized by an alkali to silica ratio that is so low as to minimize uptake of water and swelling, or because of alkali leaching from the bars (ASTM C227).

### *ASTM C289-07, Quick Chemical Method, 1952*

ASTM C289 was originally approved in 1952. Last edition revised/approved in 2007 as C289 – 07. This method consists of crushing the aggregate source to 150 to 300 µm (No. 100 to No. 50 sieve) particles and then immersing it in a 1N NaOH solution at 80°C (176°F) for 24 hours. The solution is then filtered and analyzed for the content of dissolved silica (Sc) and reduction in alkalinity (Rc) which are both plotted on a standard graph defining areas of innocuous, deleterious, and potentially reactive aggregates.

The quick chemical test has been extensively evaluated [Mielenz et al., 1948; Mielenz et al., 1950; Mielenz et al., 1958]. Correlations exist between the quick chemical test, and expansion of mortar bars made with high-alkali cement, petrographic examination of aggregates, and field performance. These correlations provided the basis for establishing the divisions on the graph used in ASTM C289 to classify an aggregate with respect to potential for reactivity.

Many aggregates are not adequately identified using this test. A significant number of known alkali-silica reactive aggregates pass the test while many innocuous aggregates are identified as deleterious. The poor performance of this testing method can be blamed on 1) the interference of minerals such as calcium, magnesium, silicates, gypsum, zeolites, clay minerals, organic matter, or iron oxides and 2) the crushing and preparation of the aggregates especially with aggregates containing microcrystalline quartz (Berube, and Fournier 1993).

### *The Conrow test, 1952, ASTM C342, 1954- withdrawn -2001*

Standard Test Method for Potential Volume Change of Cement-Aggregate Combinations—This test method, described in ASTM C342, is essentially a modified mortar-bar expansion test to determine potential expansion of a particular cement- aggregate combination due to a number of mechanisms, including ASR. It had been used primarily for research on aggregates in Oklahoma, Kansas, Nebraska, and

Iowa (Conrow 1952). The test involves subjecting mortar bars to varying moisture and temperature storage conditions, and periodically measuring length change for up to one year. ASTM C342 states that no acceptance limits for expansion have been established for this procedure. However, ASTM subcommittee work has indicated that expansion equal to or greater than 0.020 percent after one year may indicate unacceptable expansions due to alkali-silica reaction. ASTM C342-97 was withdrawn in 2001.

### ***ASTM C295, Petrographic Examination of Aggregates, 1954***

ASTM C295 was originally approved in 1954 and the last revised/approved version was released in 2008 as ASTM C295 – 08. Equivalent RILEM standard and British standards are AAR-1 and BS 812: Part 104, respectively. This method was based on the work conducted by Mather (Mather et al., 1950), “Method of Petrographic Examination of Aggregates for Concrete”. Petrographic examinations are made to determine the physical and chemical characteristics of the material; to describe and classify the constituents of the sample, to determine the relative amounts of the constituents of the sample that are essential for proper evaluation of the sample when the constituents differ significantly in properties that have a bearing on the performance of the material in its intended use; and to compare samples of aggregate from new sources with samples of aggregate from one or more sources, for which test data or performance records are available. In a RILEM technical committee TC106 survey (RILEM 1993), it was found that most countries rated the petrographic examination as an essential screening test.

The petrographic examination of aggregate samples provides a quick and reliable way to identify potentially reactive aggregate types. The tests may involve visual and microscopic examination of prepared samples— examining thin sections of aggregates using an optical microscope, sieve analysis, microscopy, scratch or acid tests. In some cases, the petrographic analysis can be completed using techniques such as X-ray diffraction, scanning electron microscopy (SEM), or IR spectroscopy. A petrographic examination is a useful screening procedure that can be done early in the development and testing of a new aggregate source and as a periodic check of operating deposits. ASTM C295 specifically recommends that the petrographer identify and call attention to potentially alkali-silica reactive constituents. The examination, however, cannot predict if potentially reactive materials are indeed deleteriously expansive.

This test method suffers from the following limitations:

- The test needs an experienced petrographer.
- A microscopic analysis is a more involved and time-consuming procedure. Hence, this analysis will typically use a smaller aggregate sample and therefore precautions must be taken to ensure that the sample is representative of the source.
- The results of a petrographic analysis will not reveal whether an aggregate will cause deleterious expansion in concrete; this needs to be evaluated using other test methods.
- Research and experience has indicated that petrographic analysis can fail to identify slowly reactive aggregates (Technical Services Center, 2009).

### *ASTM C1293, Concrete Prism Test, 1950s*

In 1973, a concrete prism expansion test was introduced in Canada. This test had been developed by Swenson and Gillott in the 1950's (Swenson and Gillott, 1964) to identify the alkali-carbonate reactive rocks found in southern Ontario, Canada. ASTM C1293, Test Method for Determination of Length of Change of Concrete Due to Alkali- Silica Reactivity (Concrete Prism Test) was originally approved in 1995. Current edition is ASTM C1293-08b. The current version of the Canadian concrete prism test [CSA (2000)], which has been adopted by ASTM (as ASTM C1293), uses a cement content of 420 kg/m$^3$ (708 lbs/yd$^3$) with the cement alkalis raised to 1.25% Na2Oeq by the addition of NaOH to the mix water. The concrete prisms, 3 in. x 3 in. x 11.25 in. (75 mm x 75 mm x 285 mm), are stored over water in sealed containers at 100°F (38°C). Aggregates are considered acceptable if the average expansion of concrete prisms is less than 0.040% at 1 year. For mitigation, material combinations are considered acceptable if the average expansion of concrete prisms is less than 0.040% at 2 years.

The Canadians have experienced that due to leaching, concrete prisms exhibited less expansion than concrete blocks stored outside that have the same aggregates and same level of alkalis. Research has shown that approximately 35% of the alkalis originally in the concrete prism leach out into the water reservoir after 1 year, and as much as 20% after just 90 days (Thomas et al. 2006).

The concrete prism test is used to assess both fine and coarse aggregate in concrete. Equivalent Canadian, RILEM and British standards are CSA A23.2-14A, RILEM TC191-ARP-03 and BS 812: Part 123, respectively.

The two major limitations of this test are as follows:

- Long Test Duration: The CPT requires at least one year or two years, depending upon the purpose of this test and as such is impractical for screening aggregates for a specific project and evaluating ASR mitigation measures, particularly in case of projects with a short construction schedule.
- Alkali Leaching: During the course of the test in the CPT method, the alkalis in concrete prisms can potentially leach out of the prisms due to convective air currents that develop within the storage container. As a result, the CPT prism specimens can exhibit less expansion than their corresponding concrete blocks stored outside with the same level of alkalis. Indeed, as much as 20% of the alkalis originally in the concrete prism leach out into the water reservoir after just 90 days, and approximately 35% leach out after 1 year (Thomas et al. 2006).

### *Osmotic Cell Tests, 1955*

A simple test method that combines both physical and chemical effects of ASR is the osmotic cell test was developed by Verbeck and Gramlich (1955). Its use eliminates the mechanics of materials effects that complicate mortar and concrete test data. Osmotic cell pressure uses swelling pressure by dissolution, and has been used for a separate study of certain variables and the direct observation and control of some of the chemical and physical aspects of the reaction mechanism. Later progress had been made by Stark and Schmitt in development of the test to determine potential reactivity of aggregates (Stark, 1983). The limitation of this test is that, in real structure osmotic cells can develop without ASR gel.

### ***Gel Pat Test, 1958***

The gel pat test originated in England as a qualitative method to characterize ASR (National Building Studies, 1958). In the gel pat test, pieces of the aggregate being tested are cast into cement paste pats, which, after curing, are ground to expose the aggregate surfaces. The smooth, sawn surface of a mortar specimen containing the test aggregate is immersed in alkali solution for a period of three days. If the aggregate is reactive, gel forms along the reacted particles, and the percentage of reactive constituents can be estimated. The test can be a simple means of evaluating an aggregate's potential for ASR (Fournier and Berube, 1993), despite its lack of quantitative measurements. However, the test does not provide a quantitative measurement of the aggregate reactivity and as such does not render itself as a suitable method for standardization.

### ***Rock cylinder method, 1966***

The rock cylinder method (ASTM C586) was designed to evaluate the potential reactivity of alkali reactive carbonate aggregates, but it has also been used with varying degrees of success to evaluate the alkali Silica reactivity. This test is based on work by Hadley (1964) and indicates whether a rock will expand when exposed to an alkaline solution. ASTM C586 was originally approved in 1966.

### ***Concrete Cube Test, 1973***

The concrete cube test, also known as the “Dahms cube test,” was first developed and used in Germany (Bonzel and Dahms, 1973 and Dahms, 1977). The cube test is a qualitative method whereby 300 mm concrete cubes made with test aggregate are periodically inspected for cracking and gel exudations due to ASR. The cubes are stored in a moist room (≥ 95 percent RH) maintained at 40°C. An alternative method is to cast 100 mm cubes and store them at 65 percent relative humidity and 20°C, with partial immersion in water. British and South African investigators use variations of this test (Grattan-Bellew 1983). This test method does not provide a quantitative measurement and is not suitable as a standardized test method for screening aggregate.

### ***Nordtest Accelerated Alkali-Silica Reactivity Test, Saturated NaCl bath method, 1978***

This method was first developed by Jensen and Chatterji (JENSEN, et al. 1982) and has become known as Nordtest Building Method 295. The test is one of several modified, accelerated mortar-bar expansion tests. The method is intended to identify reactive fine aggregate that is problematic in Denmark. In this method, three mortar prisms are first water cured for 27 days. After that, they are stored in a saturated NaCl solution bath at 50°C. The size of the prisms is fixed at 40 by 40 by 160 mm. Sand to cement ratio is fixed at 3 and the water to cement ratio of the mortar is fixed at 0.5. Comparator readings are taken periodically for a period of eight weeks or more. However, this test method is limited to evaluating fine aggregates. Also, considering that the driver of the reaction in this test is NaCl solution and not an alkali hydroxide solution, it is likely that the composition of Portland cement is important in this test.

### *JIS A1146, Mortar Bar Test Method, Japanese Industrial Standard (JIS)*

In the Japanese Industrial Standard method, the alkali content of the cement is adjusted to 1.2% by adding required amount of 1 N NaOH to mixing water. The mixture proportion of the mortar is- water: cement: aggregate = 0.5:1.0:2.0. Three mortar bar specimens are cast for each cement–aggregate combination. The initial lengths of the mortar bars are measured immediately after removing the mold. They are then placed in the fog container, which is maintained at temperature of 40°C and relative humidity (RH) of 100% for a period of 6 months. The lengths of the mortar bars are measured at weekly intervals. This method suffers from a long test duration of six months required to obtain a result.

### *Chinese Autoclave Test (CES 48:93), Japanese autoclave test, 1983*

The Chinese autoclave method was proposed by Tang et al. (1983). Chinese autoclave test (CES 48:93) method is performed at 150°C and requires only one day. Bar size (10 by 10 by 40 mm). Expansion criterion is 0.10% at 6 h. However, many of the slowly reactive aggregates are not identified in this method.

### *ASTM C1260, Accelerated mortar bar test (AMBT); South African mortar-bar test- Oberholster and Davies, 1986*

The accelerated mortar bar test (AMBT) was developed by Oberholster and Davies (1986) at the National Building Research Institute (NBRI) in the Republic of South Africa. This test is a modification of ASTM C227, where in 50 mm x 50 mm x 285 mm (1 in. x 1 in. x 11.25 in.) mortar bars are prepared using a standard aggregate gradation. The Portland cements meeting the requirements of ASTM C150 can be used in this test; however, the autoclave expansion of the cement is limited to 0.20%.

The test involves the immersion of mortar bars in 1N NaOH solution at 800°C (1760°F) for 14 days. This test produces results within 16 days from the time of casting. The test was originally approved in 1989 and revised/reapproved in 2007 as ASTM C1260 – 07. It was also approved in Canada in 1994 by CSA A23.2-25A (94). Equivalent RILEM standard is AAR-2, and British standard is DD 249: 1999.

Coarse aggregates can be evaluated in this test method; however, they have to the crushed to sand size (< 5 mm) and then washed and graded to meet the grading requirements of the test. Sands have to be washed and graded to meet the same grading requirements. The test is intended to evaluate coarse and fine aggregates separately, and should not be used to evaluate job combinations of coarse and fine aggregates.

Mortar bar expansions of less than 0.10% at 16 days after casting are indicative of innocuous behavior in most cases. If the average expansion is greater than 0.10% but below 0.20%, the aggregate may be slowly reactive. Aggregates that exhibit expansion in this range are known to be both innocuous and deleterious in field performance and additional confirmatory tests should be performed. If average expansion exceeds 0.20 percent, the aggregate is considered deleteriously reactive.

This test method has been known to produce false positive and false negative results. A false positive test result is one when the test identifies an aggregate as deleterious; however, its performance in field is good. Even though this test is capable of detecting reactive aggregates, it was also found to be too severe on a large number of aggregates that have performed well in the field as well as in the concrete prism method, ASTM C1293. In particular, the aggregates that tend to be mischaracterized in this test method include greywackes, lithic gravels, some hornfelses, gabbros, and and esites (Bérubé and Fournier 1993).

A false negative test result is one when the test identifies an aggregate as innocuous; however, the aggregate is found to be deleteriously reactive in the field. Generally, false negative results are not as common as false positive results in this test; however, there appears to be an increasing number of coarse aggregates, e.g. four coarse aggregates reported by Folliard (2006) that pass the ASTM C1260 test but fail the ASTM C1293 test. False negative cases were recently reported with aggregates such as granitic- gneiss, metadacite, granodiorite among others in which AMBT indicates a nonreactive aggregate, but in which concrete containing the aggregate has been found to be reactive in both the field and in the CPT method [Folliard et al. 2006].

Although this test method is widely adopted in practice, it has some major limitations. These include the following:

- Excessive Manipulation/Crushing of Aggregates: Coarse aggregates must be crushed to sand size (< 4.75 mm) and then washed and graded to meet the grading requirements of the test. Excessive crushing may alter the availability of reactive silica within the matrix of the aggregate and therefore the reactivity of the aggregate.
- High Test Temperature: A storage temperature of 800°C is a requirement, which is too high for typical field exposure conditions, thereby causing unrealistic levels of expansion in the test specimens.
- Job Mix: This test method cannot be employed to evaluate a particular concrete mixture with specific combination of cement, admixtures and aggregates.

False Positives and False Negative Test Results: The excessive proportion of false positive and false negative test results in this method limits the effectiveness of AMBT in reliably evaluating aggregate reactivity [Berube et al., 1993; Berube et al., 1992; Fournier and Berube 2000; DeMerchant et al., 2000; Marie et al., 2000, Chau et al., 2004; Folliard et al. 2006].

### *The Simple Chemical Method, 1989*

It is based on a fundamental consideration of the reaction mechanism of alkali– silica reaction. In this method 100 g aggregate, in its natural state, is digested at 70°C in a suspension of $Ca(OH)_2$ in saturated KCl for 16 h. The nascent $CaCl_2$ depresses the solubility of $Ca(OH)_2$ in solution. The difference in $Ca(OH)_2$ contents of the test mixture and a control mixture with a non-reactive quartz sand corresponds to the amount of K+ that has entered in the hydrated lime–alkali–silica complex. The difference is determined by titrating the two solutions with HCl. This proposed method has a number of advantages. The method is simple and does not need complicated instruments. It can be carried out in a quarry and result is obtained generally within 24 h (Chatterji, 1989). However, this test method has the limitation of no quantitative measurement in terms of degree of reactivity or the level of potential damage in concrete.

### *Autoclave Mortar Bar Test, 1991*

Fournier et al. (1991) developed a rapid autoclave test for mortar bars that provides results in a few days. The mortar bars are made according to ASTM C227 specifications, except that a fixed w/c of 0.5 is maintained, and the alkali content of the mortar is raised to 3.5 percent by the addition of NaOH to the mixing water. The bars are stored at 100 percent relative humidity at 23°C for two days before autoclave treatment. The autoclave procedure follows ASTM C151, except that the steam curing is five hours at 130°C and 0.17 MPa. Only two length measurements are taken, one after two days of moist curing and the second when the bars have been cooled to 23°C after autoclave treatment.

### *Accelerated Concrete Prism Test, 1992*

In 1992, Ranc and Debray proposed accelerating the rate of expansion in the concrete prism test (ASTM C1293) and, hence shortening its duration by increasing the exposure temperature to 60°C (140°F). Since then, there have been a number of studies on the accelerated test and it was proposed that a three-month expansion limit of 0.040% would be suitable for identifying reactive aggregates. Subsequent research conducted to correlate this accelerated concrete prims test with standard concrete prism test yielded conflicting findings. Thomas et al. found that the 3-month expansion results in the accelerated concrete prism tests showed good correlation ($R^2 = 0.9808$) with results from the 1-year long standard concrete prism test (Thomas et al. 2006). However, this test method also suffers from the concerns similar to CPT such as leaching of alkalis from the concrete prisms. Also, the test duration is still somewhat longer with a requirement of expansion limit of 0.040% at 3-months (13-weeks).

### *Japanese autoclave test is JIS A 1804*

The rapid test method JIS A 1804 for identification of the alkali reactivity of aggregates was published on 1 March 1992 in Japan. This method is one of the standard test method series for production control of concrete designated as JIS A 1800s (Koichi 1994). Mortar bar specimens made of crushed sample aggregate, standard sand, cement and NaOH solution are placed in boiling water in a pressure vessel (gauge-pressure 0·15 MPa, temperature 127°C) for 4 h after a 2-day curing. Alkali reactivity of an aggregate is evaluated by any one of the following three items: ultrasonic pulse velocity ratio, relative dynamic modulus of elasticity and length change between, before and after the boiling. This test is limited by similar shortcomings as ASTM C1260 test method.

### *Modified gel pat test, Fournier, 1993*

A modified gel pat test was developed in which polished concrete slices, 75 mm × 75 mm × 25 mm in size, were immersed in a 1N NaOH solution at 38°C for 56 days. A rating system, called the gel pat test rating (GPTr), was then developed to quantify the amount of gel formed on the polished concrete sections. The basic parameters used are (1) the proportion of particles showing gel deposits on their surface, and (2) the average amount of gel formed at the surface of the particles. The method was applied to 65 samples of carbonate aggregates from the St Lawrence Lowlands of Quebec (Canada).

Fairly good correlations were obtained between the GPTr and the results of various test methods currently used to evaluate the potential alkali-reactivity of concrete aggregates in Canada. (Fournier, B., and Berube, M. A. (1993).

### ***Chinese Accelerated Mortar Bar Method—CAMBT***

It was developed in China by combining the advantages of the Chinese autoclave method and the AMBT method (Xu Zhongzi, 1998). In the CAMBT, a single size fraction of fine aggregate (0.15–0.80 mm) and a high-alkali system of 1.5% Na2Oeq (obtained through the addition of KOH to a low-alkali cement) are used, which are the same as in the Chinese autoclave test.

### ***Chinese Concrete Microbar Test (RILEM AAR-5), 1999***

Chinese Accelerated Concrete Microbar Method was developed by Nanjing University of Chemical Technology, China, (Xu et al., 1999). It evaluates alkali-silica reaction expansions by using aggregate having particles size between 4.75 and 12.5 mm (No. 4 and 1/2 in.), a water-cement ratio (w/c) of 0.33, and an aggregate-cement ratio of 1:1. Prismatic 40 mm x 40 mm x 160 mm (1.58 in. x 1.58 in. x 6.30 in.) microbar specimens are stored at 80 °C (176 °F) in 1 N NaOH solution similar to that applied in the AMBT. Materials: 900 g of cement, 900 g of 4/8 mm aggregate, and 290 ml of water for each batch for three concrete bars. Length measurements are taken at 1, 2 days (or 3 or 4 days), 7 days, 14 days, 21 days and 28 days.

### ***Modified Versions of ASTM C1260 and ASTM C1293 Test to Evaluate ASR Potential of Recycled Concrete, 2000***

ASR of field pavement cores and recycled concrete aggregate (RCA) was investigated using techniques and procedures to accelerate the standard ASTM C1260 and ASTM C1293 tests normally utilized to evaluate conventional aggregate by Gress et al. (2000). Laboratory RCA concrete testing included evaluating prisms and cubes with and without holes added to increase the surface to volume ratios and variable moisture storage conditions such as placing the specimens in evacuated bags with surface water. Standard 280 mm (11 in) prisms with 76.2 mm (3 in) faces, cast with four 6.35 mm (0.25 in) parallel longitudinal holes were shown to accelerate ASR. The expansions of concrete 76.2 mm (3 in) cubes were found to be much higher than standard prisms at any given time. Modified versions of ASTM C1260 and ASTM C1293 were found to effectively accelerate ASR.

### ***Universal Accelerated Test for Alkali-Silica and Alkali-Carbonate Reactivity of Concrete Aggregates, 2008***

This test method was based on modifications to the Chinese Microbar Test Method. In this test method a single size fraction of 2.5–5.0 mm aggregate particles is used. Three bars, 40 mm x 40 mm x 160 mm, made at fixed cement-aggregate ratio of 1:1, and water-cement ratio of 0.33 are used and the length change of the bars is monitored till 28 days in 1 M NaOH solution at 800 C after being soaked in 800°C waterfor 24 h. The acceptance criterion is 0.093% at 14 days (Duyou, Fournier et al., 2008). The shortcomings of this test method are similar to that of the ASTM C1260 method.

# Appendix B
# Concrete Mix Design

## Example Concrete Mix Design of MCPT Specimens

### Volume and Weight of 3 MCPT Specimen

| | | |
|---|---|---|
| Nominal size: | 2 in. x 2 in. x 11.25 in. | |
| Volume of 3 specimens: | 0.078125 | ft$^3$ |
| | or, 0.00221225 | m$^3$ |
| | or, 2.21225 | L |
| | | |
| Volume of 3 specimens with Wastage: | 0.09765625 | ft$^3$ |
| | or, 0.002765313 | m$^3$ |
| | or, 2.7653125 | L |
| Weight of 3 specimens: | or, 6.658 | kg |
| | or, 6658 | g |

### Amount of Cement and Water Required

| | | |
|---|---|---|
| Cement content: | 420 | kg/m3 |
| Specific gravity of non-air-entrained type 1 cement: | 3.15 | |
| Density of water: | 1000 | kg/m3 |
| Cement required for 3 Specimens: | 0.929 | kg |
| | or, 929 | g |
| Volume of Cement: | 0.000294967 | m3 |
| w/c ratio: | 0.45 | (TP-110) |
| Water required for 3 Specimens: | 0.418 | kg |
| | or, 418 | g |
| Volume of water: | 0.000418115 | m3 |

### Final Volume and Weight of Concrete Mix

| | | |
|---|---|---|
| Maximum Aggregate Size: | 9.5 | mm |
| | or, 0.374 | in |
| Allowable Slump: | 75 | mm |
| | or, 3 | in |

According to ACI mix design, for non-air-entrained concrete, the air content is 3 percent of total concrete volume

| | | |
|---|---|---|
| Air content: | 3 | % |
| | or, 0.00234375 | ft$^3$ |
| | or, 6.63675E-05 | m$^3$ |

| | | |
|---|---|---|
| Final volume of 3 specimens w/o air content: | 0.07578125 | ft$^3$ |
| | or, 0.002145883 | m$^3$ |
| | or, 2.1458825 | L |
| Final weight of 3 specimens w/o air content: | 5.167 | kg |
| | or, 5167 | g |

**Coarse Aggregate Quantity**

| | | |
|---|---|---|
| Volume of Coarse aggregate per unit volume of concrete: | 0.65 | (TP-110) |
| Volume of Coarse Aggregate (CA) required for 3 samples: | 0.001394824 | m3 |

**Table B 1. Coarse Aggregate Grading Requirements**

| Sieve passing | Sieve Retained | Mass % |
|---|---|---|
| 12.5mm (1/2 in.) | 9.5 mm (3/8 in.) | 57.5 |
| 9.5 mm (3/8 in.) | 4.75 mm (No. 4) | 42.5 |

| | | |
|---|---|---|
| Bulk density of 9.5 mm aggregates | 1518 | kg/m$^3$ |
| Weight of 9.5 mm coarse aggregates required for 3 MCPT Bars: | 1.217 | kg |
| | or, 1217 | g |
| Bulk density of 9.5 mm aggregates | 1592 | kg/m$^3$ |
| Weight of 4.75 mm coarse aggregates required for 3 MCPT Bars: | 0.944 | kg |
| | 944 | g |

**Fine Aggregate Volume and Quantity**

| | | |
|---|---|---|
| Volume of Fine Aggregate required for 3 specimens | 0.000037977 | m$^3$ |
| Fine Aggregate required for 3 specimens | 1658 | g |

**Table B 2. Individual Sieve Weight of Fine Aggregate Based on ASTM C 33 Gradation**

| Sieve Size | Individual weight % | Individual weight (g) | Percent of individual fraction retained by mass (ASTM C 1260) | Cumulative Percent retained by mass |
|---|---|---|---|---|
| 2.36-mm (No. 8) | 10 | 166 | 10 | 10 |
| 1.18-mm (No. 16) | 25 | 415 | 25 | 35 |
| 600-µm (No. 30) | 25 | 415 | 25 | 60 |
| 300-µm (No. 50) | 25 | 415 | 25 | 85 |
| 150-µm (No. 100) | 15 | 249 | 15 | 100 |
| | | | **Total** | **290** |
| | | | **F.M** | **2.9** |

*Note: (According to AASHTO TP-110 F.M should be 2.6 ± 0.3). So F.M 2.9 is OK*

### NaOH required for Concrete Mix: Cement-Only Mixtures (no SCM)

According to AASHTO TP 110, 1.898 kg/m3 NaOH required to achieve a total alkali content of 1.25 percent of Na2O in 1 m3 of concrete

| | | |
|---|---|---|
| NaOH required for 3 MCPT specimens concrete mix | 0.004072885 | kg |
| | 4.073 | g |

### NaOH required to soak the specimens

According to AASHTO TP 110, 1L soak solution consists 900ml water+ 40g NaOH + additional distilled water needed to obtain 1L solution.

| | | |
|---|---|---|
| For soaking 3 MCPT specimens solution required: | 5 | L |
| So, NaOH required to soak 3 specimens: | 200 | g |
| Water required to soak 3 specimens: | 4500 | ml |
| Distilled water required to soak 3 specimens: | 300 | ml |

# Appendix C

# MCPT Specimen Laboratory Datasheet

## Measured Length and Weight Data of MCPT Specimens: Boise State University

**Table C 1. Length and Weight Data of MCPT Specimens: El - 116 (C.A)**

| Day | Date | Time | Specimen Length Measurement (in) | | | Specimen Weight Measurement (g) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 |
| Sample Preparation | May 15, 2019 | 2:45 PM | - | - | - | - | - | - |
| Initial Length | May 16, 2019 | 2:30 PM | 10.0000 | 10.0000 | 10.0000 | 1925.5 | 1918.5 | 1943.6 |
| Zero day | May 17, 2019 | 2:30 PM | 10.0000 | 10.0000 | 10.0000 | 1933.6 | 1927.7 | 1952.5 |
| 3 | May 20, 2019 | 2:30 PM | 10.0000 | 10.0000 | 10.0000 | 1937.8 | 1932.9 | 1956.8 |
| 7 | May 24, 2019 | 2:30 PM | 10.0021 | 10.0000 | 10.0005 | 1942.7 | 1936.9 | 1961.1 |
| 10 | May 27, 2019 | 2:30 PM | 10.0033 | 10.0000 | 10.0016 | 1942.9 | 1937.4 | 1962.3 |
| 14 | May 31, 2019 | 2:30 PM | 10.0046 | 10.0024 | 10.0038 | 1943.1 | 1938.8 | 1964.0 |
| 21 | June 7, 2019 | 2:30 PM | 10.0090 | 10.0052 | 10.0069 | 1946.0 | 1939.6 | 1965.4 |
| 28 | June 14, 2019 | 2:30 PM | 10.0135 | 10.0075 | 10.0094 | 1946.2 | 1939.7 | 1965.3 |
| 42 | June 28, 2019 | 2:30 PM | 10.0131 | 10.0091 | 10.0107 | 1945.1 | 1938.9 | 1966.1 |
| **56** | **July 12, 2019** | **2:30 PM** | **10.0161** | **10.0120** | **10.0133** | **1943.3** | **1936.8** | **1963.7** |

**Table C 2. Length and Weight Data of MCPT Specimens: El - 116 (F.A)**

| Day | Date | Time | Specimen Length Measurement (in) | | | Specimen Weight Measurement (g) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 |
| Sample Preparation | April 19, 2019 | 2:00 PM | - | - | - | - | - | - |
| Initial Length | April 20, 2019 | 2:20 PM | 10.0000 | 10.0000 | 10.0000 | 1914.7 | 1915.4 | 1924.8 |
| Zero day | April 21, 2019 | 2:20 PM | 10.0000 | 10.0000 | 10.0000 | 1922.9 | 1924.4 | 1938.5 |
| 3 | April 24, 2019 | 2:20 PM | 10.0000 | 10.0000 | 10.0000 | 1928.9 | 1931.8 | 1947.7 |
| 7 | April 28, 2019 | 2:20 PM | 10.0124 | 10.0142 | 10.0073 | 1934.9 | 1936.5 | 1952.9 |
| 10 | May 1, 2019 | 2:20 PM | 10.0220 | 10.0232 | 10.0146 | 1938.7 | 1940.5 | 1956.6 |
| 14 | May 5, 2019 | 2:20 PM | 10.0290 | 10.0312 | 10.0228 | 1941.9 | 1943.3 | 1958.7 |
| 21 | May 12, 2019 | 2:20 PM | 10.0533 | 10.0549 | 10.0451 | 1945.5 | 1946.6 | 1962.0 |
| 28 | May 19, 2019 | 2:20 PM | 10.0609 | 10.0528 | 10.0517 | 1946.6 | 1948.4 | 1963.9 |
| 42 | June 2, 2019 | 2:20 PM | 10.0695 | 10.0715 | 10.0596 | 1949.3 | 1950.9 | 1965.9 |
| **56** | **June 16, 2019** | **2:20 PM** | **10.0749** | **10.0789** | **10.0657** | **1951.3** | **1952.8** | **1967.8** |

**Table C 3. Length and Weight Data of MCPT Specimens: ORE – 8c (C.A)**

| Day | Date | Time | Specimen Length Measurement (in) | | | Specimen Weight Measurement (g) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 |
| Sample Preparation | May 13, 2019 | 2:15 PM | - | - | - | - | - | - |
| Initial Length | May 14, 2019 | 2:15 PM | 10.0000 | 10.0000 | 10.0000 | 1858.2 | 1907.8 | 1886.0 |
| Zero day | May 15, 2019 | 2:15 PM | 10.0000 | 10.0000 | 10.0000 | 1872.3 | 1919.2 | 1898.2 |
| 3 | May 18, 2019 | 2:15 PM | 10.0000 | 10.0000 | 10.0000 | 1886.0 | 1928.3 | 1910.7 |
| 7 | May 22, 2019 | 2:15 PM | 10.0000 | 10.0000 | 10.0001 | 1885.3 | 1928.4 | 1905.7 |
| 10 | May 25, 2019 | 2:15 PM | 10.0000 | 10.0000 | 10.0025 | 1882.6 | 1928.8 | 1906.2 |
| 14 | May 29, 2019 | 2:15 PM | 10.0000 | 10.0000 | 10.0046 | 1883.7 | 1930.1 | 1907.7 |
| 21 | June 5, 2019 | 2:15 PM | 10.0024 | 10.0045 | 10.0060 | 1884.5 | 1931.3 | 1907.5 |
| 28 | June 12, 2019 | 2:15 PM | 10.0036 | 10.0070 | 10.0129 | 1884.3 | 1931.0 | 1907.8 |
| 42 | June 26, 2019 | 2:15 PM | 10.0074 | 10.0116 | 10.0172 | 1884.7 | 1931.5 | 1907.6 |
| **56** | **July 10, 2019** | **2:15 PM** | **10.0092** | **10.0155** | **10.0209** | **1882.4** | **1930.1** | **1906.5** |

**Table C 4. Length and Weight Data of MCPT Specimens: ORE – 8c (F.A)**

| Day | Date | Time | Specimen Length Measurement (in) | | | Specimen Weight Measurement (g) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 |
| Sample Preparation | April 13, 2019 | 10:30 PM | - | - | - | - | - | - |
| Initial Length | April 14, 2019 | 11:00 PM | 10.0000 | 10.0000 | 10.0000 | 1896.9 | 1928.2 | 1888.6 |
| Zero day | April 15, 2019 | 11:00 PM | 10.0000 | 10.0000 | 10.0000 | 1905.2 | 1937.3 | 1902.4 |
| 3 | April 18, 2019 | 11:00 PM | 10.0100 | 10.0081 | 10.0165 | 1916.6 | 1947.8 | 1915.4 |
| 7 | April 22, 2019 | 11:00 PM | 10.0341 | 10.0316 | 10.0386 | 1922.7 | 1954.0 | 1920.7 |
| 10 | April 25, 2019 | 11:00 PM | 10.0370 | 10.0323 | 10.0403 | 1926.8 | 1957.3 | 1923.7 |
| 14 | April 29, 2019 | 11:00 PM | 10.0467 | 10.0410 | 10.0483 | 1930.1 | 1960.3 | 1926.2 |
| 21 | May 6, 2019 | 11:00 PM | 10.0585 | 10.0535 | 10.0579 | 1934.1 | 1964.3 | 1930.0 |
| 28 | May 13, 2019 | 11:00 PM | 10.0807 | 10.0759 | 10.0802 | 1936.6 | 1967.0 | 1932.6 |
| 42 | May 27, 2019 | 11:00 PM | 10.0917 | 10.0863 | 10.0905 | 1940.1 | 1971.3 | 1936.3 |
| **56** | **June 10, 2019** | **11:00 PM** | **10.1033** | **10.0978** | **10.1015** | **1942.7** | **1973.8** | **1938.7** |

### Table C 5. Length and Weight Data of MCPT Specimens: Md – 45c (C.A)

| Day | Date | Time | Specimen Length Measurement (in) | | | Specimen Weight Measurement (g) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 |
| Sample Preparation | May 14, 2019 | 2:15 PM | - | - | - | - | - | - |
| Initial Length | May 15, 2019 | 2:15 PM | 10.0000 | 10.0000 | 10.0000 | 1905.9 | 1874.9 | 1861.9 |
| Zero day | May 16, 2019 | 2:15 PM | 10.0000 | 10.0000 | 10.0000 | 1912.7 | 1882.2 | 1871.9 |
| 3 | May 19, 2019 | 2:15 PM | 10.0000 | 10.0000 | 10.0000 | 1919.1 | 1889.0 | 1877.7 |
| 7 | May 23, 2019 | 2:15 PM | 10.0000 | 10.0000 | 10.0000 | 1924.4 | 1894.5 | 1884.1 |
| 10 | May 26, 2019 | 2:15 PM | 10.0018 | 10.0002 | 10.0005 | 1926.1 | 1896.3 | 1886.1 |
| 14 | May 30, 2019 | 2:15 PM | 10.0070 | 10.0002 | 10.0052 | 1928.8 | 1898.3 | 1888.4 |
| 21 | June 6, 2019 | 2:15 PM | 10.0072 | 10.0002 | 10.0053 | 1928.6 | 1897.9 | 1887.9 |
| 28 | June 13, 2019 | 2:15 PM | 10.0084 | 10.0003 | 10.0067 | 1927.8 | 1896.3 | 1886.1 |
| 42 | June 27, 2019 | 2:15 PM | 10.0089 | 10.0003 | 10.0079 | 1926.0 | 1894.9 | 1885.1 |
| **56** | **July 11, 2019** | **2:15 PM** | **10.0116** | **10.0003** | **10.0097** | **1924.2** | **1892.0** | **1982.7** |

### Table C 6. Length and Weight Data of MCPT Specimens: Md – 45c (F.A)

| Day | Date | Time | Specimen Length Measurement (in) | | | Specimen Weight Measurement (g) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 |
| Sample Preparation | April 15, 2019 | 3:30 PM | - | - | - | - | - | - |
| Initial Length | April 16, 2019 | 4:00 PM | 10.0000 | 10.0000 | 10.0000 | 1897.3 | 1922.3 | 1936.1 |
| Zero day | April 17, 2019 | 4:00 PM | 10.0000 | 10.0000 | 10.0000 | 1906.8 | 1931.5 | 1946.2 |
| 3 | April 20, 2019 | 4:00 PM | 10.0004 | 10.0055 | 10.0012 | 1916.5 | 1942.8 | 1957.7 |
| 7 | April 24, 2019 | 4:00 PM | 10.0082 | 10.0134 | 10.0090 | 1922.9 | 1947.6 | 1961.4 |
| 10 | April 27, 2019 | 4:00 PM | 10.0149 | 10.0203 | 10.0146 | 1925.0 | 1949.6 | 1963.3 |
| 14 | May 1, 2019 | 4:00 PM | 10.0221 | 10.0261 | 10.0212 | 1927.1 | 1951.3 | 1964.8 |
| 21 | May 8, 2019 | 4:00 PM | 10.0309 | 10.0357 | 10.0305 | 1928.3 | 1952.7 | 1966.2 |
| 28 | May 15, 2019 | 4:00 PM | 10.0385 | 10.0430 | 10.0378 | 1928.6 | 1953.1 | 1966.3 |
| 42 | May 29, 2019 | 4:00 PM | 10.0478 | 10.0526 | 10.0467 | 1929.9 | 1954.4 | 1967.8 |
| **56** | **June 12, 2019** | **4:00 PM** | **10.0544** | **10.0587** | **10.0530** | **1936.1** | **1963.0** | **1975.9** |

**Table C 7. Length and Weight Data of MCPT Specimens: Ln – 80c (C.A)**

| Day | Date | Time | Specimen Length Measurement (in) | | | Specimen Weight Measurement (g) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 |
| Sample Preparation | June 11, 2019 | 2:30 PM | - | - | - | - | - | - |
| Initial Length | June 12, 2019 | 2:30 PM | 10.0000 | 10.0000 | 10.0000 | 1849.6 | 1910.9 | 1913.2 |
| Zero day | June 13, 2019 | 2:30 PM | 10.0000 | 10.0000 | 10.0000 | 1854.8 | 1917.1 | 1921.3 |
| 3 | June 16, 2019 | 2:30 PM | 10.0000 | 10.0000 | 10.0032 | 1858.7 | 1920.6 | 1924.7 |
| 7 | June 20, 2019 | 2:30 PM | 10.0000 | 10.0000 | 10.0043 | 1863.9 | 1925.3 | 1930.8 |
| 10 | June 23, 2019 | 2:30 PM | 10.0000 | 10.0000 | 10.0055 | 1864.5 | 1927.4 | 1933.1 |
| 14 | June 27, 2019 | 2:30 PM | 10.0000 | 10.0000 | 10.0063 | 1868.1 | 1930.4 | 1934.8 |
| 21 | July 4, 2019 | 2:30 PM | 10.0002 | 10.0005 | 10.0064 | 1870.5 | 1932.4 | 1936.5 |
| 28 | July 11, 2019 | 2:30 PM | 10.0002 | 10.0026 | 10.0075 | 1870.8 | 1932.9 | 1936.7 |
| 42 | July 25, 2019 | 2:30 PM | 10.0007 | 10.0043 | 10.0087 | 1870.2 | 1932.7 | 1935.8 |
| **56** | **August 8, 2019** | **2:30 PM** | **10.0015** | **10.0051** | **10.0096** | **1868.7** | **1931.8** | **1934.1** |

**Table C 8. Length and Weight Data of MCPT Specimens: Ln – 80c (F.A)**

| Day | Date | Time | Specimen Length Measurement (in) | | | Specimen Weight Measurement (g) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 |
| Sample Preparation | April 22, 2019 | 1:00 PM | - | - | - | - | - | - |
| Initial Length | April 23, 2019 | 1:45 PM | 10.0000 | 10.0000 | 10.0000 | 1892.9 | 1934.6 | 1911.9 |
| Zero day | April 24, 2019 | 1:45 PM | 10.0000 | 10.0000 | 10.0000 | 1896.1 | 1939.4 | 1922.8 |
| 3 | April 27, 2019 | 1:45 PM | 10.0000 | 10.0000 | 10.0000 | 1901.1 | 1944.4 | 1929.2 |
| 7 | May 1, 2019 | 1:45 PM | 10.0013 | 10.0056 | 10.0013 | 1907.0 | 1949.9 | 1935.9 |
| 10 | May 4, 2019 | 1:45 PM | 10.0106 | 10.0129 | 10.0081 | 1909.8 | 1953.2 | 1939.0 |
| 14 | May 8, 2019 | 1:45 PM | 10.0320 | 10.0332 | 10.0293 | 1913.2 | 1957.0 | 1941.7 |
| 21 | May 15, 2019 | 1:45 PM | 10.0370 | 10.0395 | 10.0344 | 1915.9 | 1966.9 | 1944.2 |
| 28 | May 22, 2019 | 1:45 PM | 10.0480 | 10.0497 | 10.0444 | 1917.3 | 1961.0 | 1945.6 |
| 42 | June 5, 2019 | 1:45 PM | 10.0582 | 10.0602 | 10.0546 | 1919.8 | 1963.4 | 1947.6 |
| **56** | **June 19, 2019** | **1:45 PM** | **10.0671** | **10.0692** | **10.0630** | **1921.0** | **1964.5** | **1948.8** |

### Table C 9. Length and Weight Data of MCPT Specimens: Bg – 111c (C.A)

| **Day** | **Date** | **Time** | **Specimen Length Measurement (in)** | | | **Specimen Weight Measurement (g)** | | |
|---|---|---|---|---|---|---|---|---|
| | | | **1** | **2** | **3** | **1** | **2** | **3** |
| Sample Preparation | April 23, 2019 | 1:15 PM | - | - | - | - | - | - |
| Initial Length | April 24, 2019 | 1:15 PM | 10.0000 | 10.0000 | 10.0000 | 1892.5 | 1916.8 | 1879.9 |
| Zero day | April 25, 2019 | 1:15 PM | 10.0000 | 10.0000 | 10.0000 | 1898.2 | 1922.7 | 1887.4 |
| 3 | April 28, 2019 | 1:15 PM | 10.0000 | 10.0000 | 10.0000 | 1901.6 | 1926.3 | 1891.0 |
| 7 | May 2, 2019 | 1:15 PM | 10.0000 | 10.0000 | 10.0000 | 1905.9 | 1930.7 | 1895.2 |
| 10 | May 5, 2019 | 1:15 PM | 10.0000 | 10.0000 | 10.0000 | 1907.3 | 1932.3 | 1896.4 |
| 14 | May 9, 2019 | 1:15 PM | 10.0000 | 10.0000 | 10.0000 | 1907.2 | 1933.8 | 1898.5 |
| 21 | May 16, 2019 | 1:15 PM | 10.0000 | 10.0041 | 10.0000 | 1909.6 | 1933.9 | 1898.1 |
| 28 | May 23, 2019 | 1:15 PM | 10.0091 | 10.0141 | 10.0021 | 1910.1 | 1934.4 | 1898.7 |
| 42 | June 6, 2019 | 1:15 PM | 10.0133 | 10.0187 | 10.0067 | 1909.3 | 1933.8 | 1897.8 |
| **56** | **June 20, 2019** | **1:15 PM** | **10.0172** | **10.0227** | **10.0106** | **1908.4** | **1932.7** | **1896.9** |

### Table C 10. Length and Weight Data of MCPT Specimens: Bg – 111c (F.A) – T1

| **Day** | **Date** | **Time** | **Specimen Length Measurement (in)** | | | **Specimen Weight Measurement (g)** | | |
|---|---|---|---|---|---|---|---|---|
| | | | **1** | **2** | **3** | **1** | **2** | **3** |
| Sample Preparation | April 6, 2019 | 4:00 PM | - | - | - | - | - | - |
| Initial Length | April 7, 2019 | 4:00 PM | 10.0000 | 10.0000 | 10.0000 | 1897.6 | 1876.5 | 1882.1 |
| Zero day | April 8, 2019 | 4:00 PM | 10.0000 | 10.0000 | 10.0000 | 1903.9 | 1880.4 | 1887.4 |
| 3 | April 11, 2019 | 4:00 PM | 10.0329 | 10.0300 | 10.0310 | 1919.5 | 1896.7 | 1903.6 |
| 7 | April 15, 2019 | 4:00 PM | 10.0367 | 10.0328 | 10.0340 | 1923.6 | 1900.5 | 1908.3 |
| 10 | April 18, 2019 | 4:00 PM | 10.0563 | 10.0507 | 10.0523 | 1926.6 | 1903.5 | 1908.3 |
| 14 | April 22, 2019 | 4:00 PM | 10.0703 | 10.0656 | 10.0657 | 1929.0 | 1905.7 | 1913.7 |
| 21 | April 29, 2019 | 4:00 PM | 10.0729 | 10.0683 | 10.0684 | 1931.4 | 1909.5 | 1916.5 |
| 28 | May 6, 2019 | 4:00 PM | 10.0824 | 10.0764 | 10.0787 | 1934.2 | 1911.3 | 1919.2 |
| 42 | May 20, 2019 | 4:00 PM | 10.0995 | 10.0968 | 10.0969 | 1937.5 | 1915.4 | 1922.8 |
| **56** | **June 3, 2019** | **4:00 PM** | **10.1219** | **10.1185** | **10.1182** | **1940.3** | **1918.1** | **1925.4** |

**Table C 11. Length and Weight Data of MCPT Specimens: Bg – 111c (F.A) – T2**

| Day | Date | Time | Specimen Length Measurement (in) | | | Specimen Weight Measurement (g) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 |
| Sample Preparation | June 13, 2019 | 1:15 PM | - | - | - | - | - | - |
| Initial Length | June 14, 2019 | 1:15 PM | 10.0000 | 10.0000 | 10.0000 | 1914.7 | 1941.5 | 1897.8 |
| Zero day | June 15, 2019 | 1:15 PM | 10.0000 | 10.0000 | 10.0000 | 1920.0 | 1947.9 | 1908.6 |
| 3 | June 18, 2019 | 1:15 PM | 10.0334 | 10.0332 | 10.0356 | 1933.7 | 1960.8 | 1923.1 |
| 7 | June 22, 2019 | 1:15 PM | 10.0563 | 10.0560 | 10.0571 | 1939.9 | 1967.6 | 1929.3 |
| 10 | June 25, 2019 | 1:15 PM | 10.0659 | 10.0649 | 10.0655 | 1943.1 | 1970.1 | 1931.7 |
| 14 | June 29, 2019 | 1:15 PM | 10.0743 | 10.0732 | 10.0736 | 1946.2 | 1973.7 | 1936.0 |
| 21 | July 6, 2019 | 1:15 PM | 10.0870 | 10.0862 | 10.0861 | 1949.2 | 1977.2 | 1939.3 |
| 28 | July 13, 2019 | 1:15 PM | 10.0974 | 10.0963 | 10.0963 | 1951.6 | 1978.7 | 1941.1 |
| 42 | July 27, 2019 | 1:15 PM | 10.1139 | 10.1135 | 10.1132 | 1956.1 | 1983.1 | 1945.9 |
| **56** | **August 10, 2019** | **1:15 PM** | **10.1269** | **10.1274** | **10.1270** | **1957.3** | **1985.1** | **1948.2** |

**Table C 12. Length and Weight Data of MCPT Specimens: Bn - 155c (C.A)**

| Day | Date | Time | Specimen Length Measurement (in) | | | Specimen Weight Measurement (g) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 |
| Sample Preparation | April 26, 2019 | 11:30 PM | - | - | - | - | - | - |
| Initial Length | April 27, 2019 | 11:30 PM | 10.0000 | 10.0000 | 10.0000 | 1900.9 | 1902.8 | 1909.2 |
| Zero day | April 28, 2019 | 11:30 PM | 10.0000 | 10.0000 | 10.0000 | 1907.4 | 1911.0 | 1917.8 |
| 3 | May 1, 2019 | 11:30 PM | 10.0000 | 10.0000 | 10.0000 | 1911.7 | 1915.1 | 1921.5 |
| 7 | May 5, 2019 | 11:30 PM | 10.0000 | 10.0000 | 10.0000 | 1916.8 | 1918.8 | 1925.5 |
| 10 | May 8, 2019 | 11:30 PM | 10.0000 | 10.0000 | 10.0000 | 1916.9 | 1920.4 | 1926.1 |
| 14 | May 12, 2019 | 11:30 PM | 10.0000 | 10.0000 | 10.0000 | 1918.6 | 1921.2 | 1927.9 |
| 21 | May 19, 2019 | 11:30 PM | 10.0000 | 10.0000 | 10.0000 | 1920.4 | 1922.8 | 1929.8 |
| 28 | May 26, 2019 | 11:30 PM | 10.0028 | 10.0066 | 10.0036 | 1920.5 | 1922.6 | 1930.1 |
| 42 | June 9, 2019 | 11:30 PM | 10.0075 | 10.0113 | 10.0081 | 1919.9 | 1921.9 | 1929.5 |
| **56** | **June 23, 2019** | **11:30 PM** | **10.0099** | **10.0141** | **10.0110** | **1918.5** | **1921.3** | **1929.0** |

### Table C 13. Length and Weight Data of MCPT Specimens: Bn - 155c (F.A)

| Day | Date | Time | Specimen Length Measurement (in) | | | Specimen Weight Measurement (g) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 |
| Sample Preparation | April 7, 2019 | 5:00 PM | - | - | - | - | - | - |
| Initial Length | April 8, 2019 | 5:00 PM | 10.0000 | 10.0000 | 10.0000 | 1891.2 | 1871.4 | 1903.1 |
| Zero day | April 9, 2019 | 5:00 PM | 10.0000 | 10.0000 | 10.0000 | 1895.7 | 1877.8 | 1907.4 |
| 3 | April 12, 2019 | 5:00 PM | 10.0285 | 10.0127 | 10.0123 | 1901.9 | 1885.2 | 1917.2 |
| 7 | April 16, 2019 | 5:00 PM | 10.0307 | 10.0277 | 10.0280 | 1907.0 | 1890.9 | 1922.1 |
| 10 | April 19, 2019 | 5:00 PM | 10.0438 | 10.0372 | 10.0370 | 1911.8 | 1894.5 | 1925.6 |
| 14 | April 23, 2019 | 5:00 PM | 10.0589 | 10.0460 | 10.0463 | 1915.6 | 1897.9 | 1928.9 |
| 21 | April 30, 2019 | 5:00 PM | 10.0628 | 10.0564 | 10.0586 | 1919.5 | 1901.3 | 1932.3 |
| 28 | May 7, 2019 | 5:00 PM | 10.0848 | 10.0627 | 10.0648 | 1922.9 | 1903.9 | 1934.2 |
| 42 | May 21, 2019 | 5:00 PM | 10.0866 | 10.0717 | 10.0748 | 1928.1 | 1908.3 | 1938.9 |
| **56** | **June 4, 2019** | **5:00 PM** | **10.1053** | **10.0830** | **10.0864** | **1928.7** | **1909.8** | **1940.7** |

### Table C 14. Length and Weight Data of MCPT Specimens: Wn - 56c (C.A)

| Day | Date | Time | Specimen Length Measurement (in) | | | Specimen Weight Measurement (g) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 |
| Sample Preparation | April 16, 2019 | 2:00 PM | - | - | - | - | - | - |
| Initial Length | April 17, 2019 | 2:00 PM | 10.0000 | 10.0000 | 10.0000 | 1987.8 | 1955.5 | 1956.2 |
| Zero day | April 18, 2019 | 2:00 PM | 10.0000 | 10.0000 | 10.0000 | 1997.2 | 1964.4 | 1965.2 |
| 3 | April 21, 2019 | 2:00 PM | 10.0000 | 10.0000 | 10.0000 | 2001.9 | 1968.5 | 1969.4 |
| 7 | April 25, 2019 | 2:00 PM | 10.0070 | 10.0044 | 10.0045 | 2005.6 | 1972.4 | 1793.9 |
| 10 | April 28, 2019 | 2:00 PM | 10.0091 | 10.0067 | 10.0074 | 2006.2 | 1973.0 | 1974.4 |
| 14 | May 2, 2019 | 2:00 PM | 10.0156 | 10.0137 | 10.0143 | 2006.9 | 1974.1 | 1975.5 |
| 21 | May 9, 2019 | 2:00 PM | 10.0178 | 10.0163 | 10.0176 | 2007.2 | 1974.0 | 1975.9 |
| 28 | May 16, 2019 | 2:00 PM | 10.0212 | 10.0199 | 10.0213 | 2007.6 | 1974.7 | 1976.6 |
| 42 | May 30, 2019 | 2:00 PM | 10.0230 | 10.0224 | 10.0237 | 2008.4 | 1975.8 | 1977.8 |
| **56** | **June 13, 2019** | **2:00 PM** | **10.0256** | **10.0253** | **10.0269** | **2008.4** | **1975.6** | **1978.0** |

**Table C 15. Length and Weight Data of MCPT Specimens: Wn - 56c (F.A)**

| Day | Date | Time | Specimen Length Measurement (in) | | | Specimen Weight Measurement (g) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 |
| Sample Preparation | June 27, 2019 | 1:00 PM | - | - | - | - | - | - |
| Initial Length | June 28, 2019 | 1:00 PM | 10.0000 | 10.0000 | 10.0000 | 1966.0 | 1952.9 | 1923.7 |
| Zero day | June 29, 2019 | 1:00 PM | 10.0000 | 10.0000 | 10.0024 | 1981.1 | 1969.8 | 1939.0 |
| 3 | July 2, 2019 | 1:00 PM | 10.0024 | 10.0021 | 10.0070 | 1991.3 | 1979.9 | 1950.7 |
| 7 | July 6, 2019 | 1:00 PM | 10.0258 | 10.0243 | 10.0301 | 1933.5 | 1982.2 | 1952.6 |
| 10 | July 9, 2019 | 1:00 PM | 10.0333 | 10.0312 | 10.0375 | 1995.7 | 1983.6 | 1954.4 |
| 14 | July 13, 2019 | 1:00 PM | 10.0505 | 10.0477 | 10.0532 | 2001.7 | 1989.7 | 1959.5 |
| 21 | July 20, 2019 | 1:00 PM | 10.0719 | 10.0704 | 10.0747 | 2006.1 | 1994.8 | 1964.4 |
| 28 | July 27, 2019 | 1:00 PM | 10.0936 | 10.0912 | 10.0923 | 2012.8 | 2001.6 | 1970.4 |
| 42 | August 10, 2019 | 1:00 PM | 10.1241 | 10.1215 | 10.1191 | 2019.6 | 2008.6 | 1977.6 |
| **56** | **August 24, 2019** | **1:00 PM** | **10.1478** | **10.1465** | **10.1444** | **2025.5** | **2016.0** | **1985.1** |

## MCPT Specimen Length and Weight Data: University of Idaho

**Table C 16. Length Data of MCPT Specimens: El - 116 (C.A)**

| Day | Specimen Length Measurement (in) | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0052 | 10.0054 | 10.0057 |
| 7 | 10.0057 | 10.0064 | 10.0063 |
| 10 | NA | NA | NA |
| 14 | 10.0064 | 10.0074 | 10.0068 |
| 21 | 10.0086 | 10.0091 | 10.0086 |
| 28 | 10.0096 | 10.0104 | 10.0090 |
| 42 | 10.0107 | 10.0120 | 10.0102 |
| **56** | **10.0114** | **10.0127** | **10.0109** |

**Table C 17. Length Data of MCPT Specimens: El - 116 (F.A)**

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0090 | 10.0092 | 10.0087 |
| 7 | 10.0293 | 10.0222 | 10.0274 |
| 10 | NA | NA | NA |
| 14 | 10.0438 | 10.0252 | 10.0444 |
| 21 | 10.0536 | 10.0559 | 10.0539 |
| 28 | 10.0599 | 10.0628 | 10.0603 |
| 42 | 10.0690 | 10.0721 | 10.0696 |
| **56** | **10.0757** | **10.0796** | **10.0760** |

**Table C 18. Length Data of MCPT Specimens: ORE – 8c (C.A)**

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0062 | 10.0061 | 10.0057 |
| 7 | 10.0079 | 10.0079 | 10.0082 |
| 10 | NA | NA | NA |
| 14 | 10.0111 | 10.0111 | 10.0110 |
| 21 | 10.0144 | 10.0144 | 10.0135 |
| 28 | 10.0167 | 10.0162 | 10.0157 |
| 42 | 10.0195 | 10.0178 | 10.0184 |
| **56** | **10.0215** | **10.0201** | **10.0206** |

**Table C 19. Length Data of MCPT Specimens: ORE – 8c (F.A)**

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0303 | 10.0297 | 10.0296 |
| 7 | 10.0502 | 10.0489 | 10.0478 |
| 10 | NA | NA | NA |
| 14 | 10.0671 | 10.0651 | 10.0640 |
| 21 | 10.0767 | 10.0748 | 10.0739 |
| 28 | 10.0840 | 10.0818 | 10.0803 |
| 42 | 10.0940 | 10.0923 | 10.0894 |
| **56** | **10.1013** | **10.0996** | **10.0960** |

**Table C 20. Length Data of MCPT Specimens: Md – 45c (C.A)**

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0069 | 10.0066 | 10.0064 |
| 7 | 10.0063 | 10.0059 | 10.0061 |
| 10 | NA | NA | NA |
| 14 | 10.0090 | 10.0089 | 10.0086 |
| 21 | 10.0101 | 10.0100 | 10.0096 |
| 28 | 10.0110 | 10.0105 | 10.0097 |
| 42 | 10.0130 | 10.0120 | 10.0110 |
| **56** | **10.0147** | **10.0138** | **10.0125** |

### Table C 21. Length Data of MCPT Specimens: Md – 45c (F.A)

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0132 | 10.0152 | 10.0132 |
| 7 | 10.0299 | 10.0332 | 10.0307 |
| 10 | NA | NA | NA |
| 14 | 10.0489 | 10.0538 | 10.0506 |
| 21 | 10.0581 | 10.0630 | 10.0606 |
| 28 | 10.0637 | 10.0686 | 10.0662 |
| 42 | 10.0709 | 10.0767 | 10.0738 |
| **56** | **10.0781** | **10.0835** | **10.0814** |

### Table C 22. Length Data of MCPT Specimens: Pw – 84c (C.A)

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0066 | 10.0067 | 10.0063 |
| 7 | 10.0073 | 10.0074 | 10.0077 |
| 10 | NA | NA | NA |
| 14 | 10.0094 | 10.0091 | 10.0096 |
| 21 | 10.0114 | 10.0105 | 10.0111 |
| 28 | 10.0129 | 10.0120 | 10.0124 |
| 42 | 10.0135 | 10.0124 | 10.0129 |
| **56** | **10.0150** | **10.0135** | **10.0139** |

### Table C 23. Length Data of MCPT Specimens: Pw – 84c (F.A)

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0078 | 10.0084 | 10.0080 |
| 7 | 10.0125 | 10.0129 | 10.0127 |
| 10 | NA | NA | NA |
| 14 | 10.0264 | 10.0281 | 10.0275 |
| 21 | 10.0343 | 10.0362 | 10.0353 |
| 28 | 10.0390 | 10.0408 | 10.0400 |
| 42 | 10.0458 | 10.0481 | 10.0469 |
| **56** | **10.0524** | **10.0547** | **10.0532** |

### Table C 24. Length Data of MCPT Specimens: Ma – 22c (C.A)

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0044 | 10.0043 | 10.0042 |
| 7 | 10.0044 | 10.0043 | 10.0043 |
| 10 | NA | NA | NA |
| 14 | 10.0053 | 10.0049 | 10.0051 |
| 21 | 10.0063 | 10.0058 | 10.0059 |
| 28 | 10.0064 | 10.0057 | 10.0063 |
| 42 | 10.0069 | 10.0061 | 10.0067 |
| **56** | **10.0087** | **10.0071** | **10.0085** |

### Table C 25. Length Data of MCPT Specimens: Ma – 22c (F.A)

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0081 | 10.0079 | 10.0069 |
| 7 | 10.0122 | 10.0122 | 10.0113 |
| 10 | NA | NA | NA |
| 14 | 10.0228 | 10.0235 | 10.0224 |
| 21 | 10.0303 | 10.0306 | 10.0303 |
| 28 | 10.0354 | 10.0354 | 10.0360 |
| 42 | 10.0453 | 10.0452 | 10.0460 |
| **56** | **10.0537** | **10.0553** | **10.0559** |

### Table C 26. Length Data of MCPT Specimens: Wn - 56 (C.A)

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0056 | 10.0060 | 10.0058 |
| 7 | 10.0062 | 10.0065 | 10.0063 |
| 10 | NA | NA | NA |
| 14 | 10.0066 | 10.0066 | 10.0074 |
| 21 | 10.0069 | 10.0071 | 10.0073 |
| 28 | 10.0074 | 10.0083 | 10.0093 |
| 42 | 10.0082 | 10.0090 | 10.0094 |
| **56** | **10.0090** | **10.0096** | **10.0105** |

### Table C 27. Length Data of MCPT Specimens: Wn - 56 (F.A)

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0030 | 10.0063 | 10.0062 |
| 7 | 10.0090 | 10.0119 | 10.0122 |
| 10 | NA | NA | NA |
| 14 | 10.0181 | 10.0203 | 10.0210 |
| 21 | 10.0293 | 10.0310 | 10.0322 |
| 28 | 10.0384 | 10.0390 | 10.0409 |
| 42 | 10.0506 | 10.0504 | 10.0536 |
| **56** | **10.0641** | **10.0625** | **10.0659** |

### Table C 28. Length Data of MCPT Specimens: Agg-1 (C.A)

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0048 | 10.0045 | 10.0047 |
| 7 | 10.0051 | 10.0048 | 10.0050 |
| 10 | NA | NA | NA |
| 14 | 10.0053 | 10.0051 | 10.0051 |
| 21 | 10.0059 | 10.0056 | 10.0057 |
| 28 | 10.0060 | 10.0057 | 10.0058 |
| 42 | 10.0071 | 10.0067 | 10.0068 |
| **56** | **10.0081** | **10.0079** | **10.0080** |

### Table C 29. Length Data of MCPT Specimens: Agg-1 (F.A)

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0046 | 10.0053 | 10.0052 |
| 7 | 10.0048 | 10.0054 | 10.0055 |
| 10 | NA | NA | NA |
| 14 | 10.0069 | 10.0074 | 10.0076 |
| 21 | 10.0093 | 10.0089 | 10.0098 |
| 28 | 10.0116 | 10.0117 | 10.0133 |
| 42 | 10.0158 | 10.0160 | 10.0185 |
| **56** | **10.0208** | **10.0209** | **10.0236** |

### Table C 30. Length Data of MCPT Specimens: Agg-3 (C.A)

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0043 | 10.0046 | 10.0043 |
| 7 | 10.0049 | 10.0052 | 10.0049 |
| 10 | NA | NA | NA |
| 14 | 10.0051 | 10.0055 | 10.0051 |
| 21 | 10.0051 | 10.0055 | 10.0051 |
| 28 | 10.0052 | 10.0055 | 10.0052 |
| 42 | 10.0059 | 10.0060 | 10.0059 |
| **56** | **10.0066** | **10.0066** | **10.0066** |

**Table C 31. Length Data of MCPT Specimens: Agg-3 (F.A)**

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0049 | 10.0054 | 10.0061 |
| 7 | 10.0059 | 10.0066 | 10.0068 |
| 10 | NA | NA | NA |
| 14 | 10.0069 | 10.0076 | 10.0078 |
| 21 | 10.0073 | 10.0081 | 10.0084 |
| 28 | 10.0079 | 10.0091 | 10.0094 |
| 42 | 10.0095 | 10.0101 | 10.0108 |
| **56** | **10.0115** | **10.0114** | **10.0117** |

**Table C 32. Length Data of MCPT Specimens: Agg-5 (C.A)**

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0012 | 10.0011 | 10.0011 |
| 7 | 10.0002 | 10.0003 | 10.0002 |
| 10 | NA | NA | NA |
| 14 | 10.0031 | 10.0031 | 10.0029 |
| 21 | 10.0014 | 10.0013 | 10.0013 |
| 28 | 10.0024 | 10.0023 | 10.0023 |
| 42 | 10.0028 | 10.0029 | 10.0027 |
| **56** | **10.0025** | **10.0026** | **10.0025** |

**Table C 33. Length Data of MCPT Specimens: Agg-5 (F.A)**

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0012 | 10.0011 | 10.0011 |
| 7 | 10.0002 | 10.0003 | 10.0002 |
| 10 | NA | NA | NA |
| 14 | 10.0031 | 10.0031 | 10.0029 |
| 21 | 10.0014 | 10.0013 | 10.0013 |
| 28 | 10.0024 | 10.0023 | 10.0023 |
| 42 | 10.0028 | 10.0029 | 10.0027 |
| **56** | **10.0025** | **10.0026** | **10.0025** |

**Table C 34. Length Data of MCPT Specimens: Agg-2 (F.A)**

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0063 | 10.0056 | 10.0052 |
| 7 | 10.0067 | 10.0058 | 10.0062 |
| 10 | NA | NA | NA |
| 14 | 10.0068 | 10.0060 | 10.0058 |
| 21 | 10.0075 | 10.0066 | 10.0068 |
| 28 | 10.0075 | 10.0065 | 10.0070 |
| 42 | 10.0097 | 10.0075 | 10.0081 |
| **56** | **10.0114** | **10.0089** | **10.0098** |

**Table C 35. Length Data of MCPT Specimens: Agg-4 (F.A)**

| **Day** | **Specimen Length Measurement (in)** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0050 | 10.0065 | 10.0060 |
| 7 | 10.0057 | 10.0071 | 10.0065 |
| 10 | NA | NA | NA |
| 14 | 10.0057 | 10.0071 | 10.0066 |
| 21 | 10.0066 | 10.0082 | 10.0074 |
| 28 | 10.0068 | 10.0084 | 10.0077 |
| 42 | 10.0077 | 10.0094 | 10.0088 |
| **56** | **10.0100** | **10.0121** | **10.0114** |

# Appendix D
# Calculation of MCPT Specimen Expansion

## Sample Calculation of MCPT Specimen Percent Expansion

**Table D 1. Sample Length Measurement Data of MCPT Specimens**

| Reading Day | Specimen Length Measurement (in) | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sample Preparation | - | - | - |
| Initial Length | 10.0000 | 10.0000 | 10.0000 |
| Zero day | 10.0000 | 10.0000 | 10.0000 |
| 3 | 10.0285 | 10.0127 | 10.0123 |
| 7 | 10.0307 | 10.0277 | 10.0280 |
| 10 | 10.0438 | 10.0372 | 10.0370 |
| 14 | 10.0589 | 10.0460 | 10.0463 |
| 21 | 10.0628 | 10.0564 | 10.0586 |
| 28 | 10.0848 | 10.0627 | 10.0648 |
| 42 | 10.0866 | 10.0717 | 10.0748 |
| **56** | **10.1053** | **10.0830** | **10.0864** |

Percent length change in test specimens at any age (X days) is calculated as follows:

$$\boldsymbol{L}\,\% = \frac{(\boldsymbol{L_x}) - (\boldsymbol{L_i})}{\boldsymbol{G}} \times \mathbf{100}$$

Here,

L = Change in length at X days, %;

$L_x$ = Comparator reading of test prism at X days minus the comparator reading of the reference bar at X days

$L_i$ = Comparator reading of test prism at zero day minus the comparator reading of the reference bar at zero day: and

G = Nominal gauge length = 10.0000 in.

Comparator Reading of Reference bar at Zero day = 10.0000 in.

Comparator Reading of Reference bar at all other (X) days = 10.0000 in.

**Table D 2. Summary of MCPT Specimen Percent Expansion**

| Days | Lx (in) | | | Li (in) | | | L% (to the nearest 0.001 percent) | | | Avg. L% (to the nearest 0.001 percent) |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | |
| Zero day | - | - | - | 0 | 0 | 0 | - | - | - | - |
| 3 | 0.0285 | 0.0127 | 0.0123 | | | | 0.285 | 0.127 | 0.123 | 0.178 |
| 7 | 0.0307 | 0.0277 | 0.0280 | | | | 0.307 | 0.277 | 0.280 | 0.288 |
| 10 | 0.0438 | 0.0372 | 0.0370 | | | | 0.438 | 0.372 | 0.370 | 0.393 |
| 14 | 0.0589 | 0.0460 | 0.0463 | | | | 0.589 | 0.460 | 0.463 | 0.504 |
| 21 | 0.0628 | 0.0564 | 0.0586 | | | | 0.628 | 0.564 | 0.586 | 0.593 |
| 28 | 0.0848 | 0.0627 | 0.0648 | | | | 0.848 | 0.627 | 0.648 | 0.708 |
| 42 | 0.0866 | 0.0717 | 0.0748 | | | | 0.866 | 0.717 | 0.748 | 0.777 |
| **56** | **0.1053** | **0.0830** | **0.0864** | | | | **1.053** | **0.830** | **0.864** | **0.916** |

# Appendix E
# AASHTO TP 110: 56-day MCPT Results for the Aggregates

**Table E 1. Summary of 56 -Day MCPT Results of the Coarse and Fine Aggregate Tested at Boise State University and University of Idaho**

| Testing Laboratory | Aggregate Name | % Expansion at 56 Days | | Reactivity Level | |
|---|---|---|---|---|---|
| | | Coarse Aggregate (CA) | Fine Aggregates (FA) | Coarse Aggregate (CA) | Fine Aggregates (FA) |
| Boise State University | El -116c | 0.138 | 0.732 | Highly Reactive | Very Highly Reactive |
| | ORE-8c | 0.152 | 1.009 | Highly Reactive | Very Highly Reactive |
| | Md-45c | 0.072 | 0.554 | Moderately Reactive | Very Highly Reactive |
| | Bg -111c | 0.168 | 1.195 | Highly Reactive | Very Highly Reactive |
| | Bn-155c | 0.117 | 0.916 | Moderately Reactive | Very Highly Reactive |
| | Ln-80c | 0.054 | 0.664 | Moderately Reactive | Very Highly Reactive |
| | Wn-56 | 0.259 | 1.454 | Very Highly Reactive | Very Highly Reactive |
| University of Idaho | El -116c | 0.117 | 0.771 | Moderately Reactive | Very Highly Reactive |
| | ORE-8c | 0.207 | 0.990 | Highly Reactive | Very Highly Reactive |
| | Md-45c | 0.137 | 0.810 | Highly Reactive | Very Highly Reactive |
| | Pw -84c | 0.141 | 0.534 | Highly Reactive | Very Highly Reactive |
| | Ma-22c | 0.081 | 0.550 | Moderately Reactive | Very Highly Reactive |
| | Wn-56 | 0.097 | 0.642 | Moderately Reactive | Very Highly Reactive |
| | Agg-1 | 0.080 | 0.218 | Moderately Reactive | Highly Reactive |
| | Agg-2 | NA | 0.100 | NA | Moderately Reactive |
| | Agg-3 | 0.066 | 0.115 | Moderately Reactive | Moderately Reactive |
| | Agg-4 | NA | 0.112 | NA | Moderately Reactive |
| | Agg-5 | 0.025 | 0.025 | Non-Reactive | Non-Reactive |

**Table E 2. Percent Expansion Value for Coarse Aggregate Materials Tested at Boise State University Using MCPT Recorded Periodically at Different Days**

| Aggregate Name | % Expansion | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Day 3 | Day 7 | Day 10 | Day 14 | Day 21 | Day 28 | Day 42 | Day 56 |
| El -116c* | 0.000 | 0.009 | 0.016 | 0.036 | 0.070 | 0.101 | 0.110 | 0.138 |
| ORE-8c* | 0.000 | 0.000 | 0.008 | 0.015 | 0.043 | 0.078 | 0.121 | 0.152 |
| Md-45c* | 0.000 | 0.000 | 0.008 | 0.041 | 0.042 | 0.051 | 0.057 | 0.072 |
| Bg -111c | 0.000 | 0.000 | 0.000 | 0.000 | 0.014 | 0.084 | 0.129 | 0.168 |
| Bn-155c | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.043 | 0.090 | 0.117 |
| Ln-80c | 0.011 | 0.014 | 0.018 | 0.021 | 0.020 | 0.034 | 0.046 | 0.054 |
| Wn-56* | 0.000 | 0.053 | 0.077 | 0.145 | 0.172 | 0.208 | 0.230 | 0.259 |

### Table E 3. Percent Expansion Value for Fine Aggregate Materials Tested at Boise State University Using MCPT Recorded Periodically at Different Days

| Aggregate Name | % Expansion | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Day 3** | **Day 7** | **Day 10** | **Day 14** | **Day 21** | **Day 28** | **Day 42** | **Day 56** |
| El -116c* | 0.000 | 0.113 | 0.199 | 0.277 | 0.511 | 0.551 | 0.669 | 0.732 |
| ORE-8c* | 0.115 | 0.348 | 0.365 | 0.453 | 0.566 | 0.789 | 0.895 | 1.009 |
| Md-45c* | 0.024 | 0.102 | 0.166 | 0.231 | 0.324 | 0.398 | 0.490 | 0.554 |
| Bg -111c | 0.313 | 0.345 | 0.531 | 0.672 | 0.699 | 0.792 | 0.977 | 1.195 |
| Bn-155c | 0.178 | 0.288 | 0.393 | 0.504 | 0.593 | 0.708 | 0.777 | 0.916 |
| Ln-80c | 0.000 | 0.027 | 0.105 | 0.315 | 0.370 | 0.474 | 0.577 | 0.664 |
| Wn-56* | 0.030 | 0.259 | 0.332 | 0.497 | 0.715 | 0.916 | 1.208 | 1.454 |

### Table E 4. Percent Expansion Value for Coarse Aggregate Materials Tested at the University of Idaho Using MCPT Recorded Periodically at Different Days

| Aggregate Name | % Expansion | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Day 3** | **Day 7** | **Day 10** | **Day 14** | **Day 21** | **Day 28** | **Day 42** | **Day 56** |
| El -116c | 0.054 | 0.061 | - | 0.069 | 0.088 | 0.097 | 0.110 | 0.117 |
| ORE-8c | 0.060 | 0.080 | - | 0.111 | 0.141 | 0.162 | 0.186 | 0.207 |
| Md-45c | 0.066 | 0.061 | - | 0.088 | 0.099 | 0.104 | 0.120 | 0.137 |
| Pw -84c | 0.065 | 0.075 | - | 0.094 | 0.110 | 0.124 | 0.129 | 0.141 |
| Ma-22c | 0.043 | 0.043 | - | 0.051 | 0.060 | 0.061 | 0.066 | 0.081 |
| Wn-56 | 0.058 | 0.063 | - | 0.069 | 0.071 | 0.083 | 0.089 | 0.097 |
| Agg-1 | 0.047 | 0.050 | - | 0.052 | 0.057 | 0.058 | 0.069 | 0.080 |
| Agg-3 | 0.044 | 0.050 | - | 0.052 | 0.052 | 0.053 | 0.059 | 0.066 |
| Agg-5 | 0.011 | 0.002 | - | 0.010 | 0.013 | 0.023 | 0.028 | 0.025 |

### Table E 5. Percent Expansion Value for Fine Aggregate Materials Tested at the University of Idaho Using MCPT Recorded Periodically at Different Days

| Aggregate Name | % Expansion | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Day 3** | **Day 7** | **Day 10** | **Day 14** | **Day 21** | **Day 28** | **Day 42** | **Day 56** |
| El -116c | 0.090 | 0.263 | - | 0.378 | 0.545 | 0.610 | 0.702 | 0.771 |
| ORE-8c | 0.299 | 0.490 | - | 0.654 | 0.751 | 0.820 | 0.919 | 0.990 |
| Md-45c | 0.139 | 0.313 | - | 0.511 | 0.606 | 0.662 | 0.738 | 0.810 |
| Pw -84c | 0.081 | 0.127 | - | 0.273 | 0.353 | 0.399 | 0.469 | 0.534 |
| Ma-22c | 0.076 | 0.119 | - | 0.229 | 0.304 | 0.356 | 0.455 | 0.550 |
| Wn-56 | 0.052 | 0.110 | - | 0.198 | 0.308 | 0.394 | 0.515 | 0.642 |
| Agg-1 | 0.050 | 0.052 | - | 0.073 | 0.093 | 0.122 | 0.168 | 0.218 |
| Agg-2 | 0.057 | 0.062 | - | 0.062 | 0.070 | 0.070 | 0.084 | 0.100 |
| Agg-3 | 0.055 | 0.064 | - | 0.074 | 0.079 | 0.088 | 0.101 | 0.115 |
| Agg-4 | 0.058 | 0.064 | - | 0.065 | 0.074 | 0.076 | 0.086 | 0.112 |
| Agg-5 | 0.011 | 0.002 | - | 0.030 | 0.013 | 0.023 | 0.028 | 0.025 |