MITIGATING ALKALI SILICATE REACTION IN RECYCLED CONCRETE

BY

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B.S., University of New Hampshire, May 2000

THESIS

Submitted to the University of New Hampshire

in Partial Fulfillment of

the Requirements for the Degree of

Master of Science

in

Civil Engineering

May, 2006

This thesis has been examined and approved.

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DEDICATION

To my parents that have always been there for guidance and given me the life tools I use everyday to make myself a better person. I think of you both everyday and hope that I can make you as proud of me as I am of you. I could not have asked for a better childhood, family, role-models, or friends. You are two very special people that have shown me through example was it means to live life to the fullest. I love you both very much.

ACKNOWLEDGEMENTS

Dr. David L. Gress has served not only as an excellent advisor through the completion of this degree, but also with his knowledge in the field of Civil Engineering and into my professional advancements. I have ever-lasting respect for his abilities as a professor, researcher, and advisor for students at the University of New Hampshire. He has taught me the importance of staying focused on goals and never being intimidated to approach projects that require persistence and hard work to complete. I appreciate all that he has done to give me the opportunity to continue my studies at the University of New Hampshire and reach the goal of a Master's of Science degree. I look forward to continuing our relationship on a professional and personal basis.

I would like to extend a special thank you to all of the people that made this project possible through research funding and development. This project would not have been possible without your contributions.

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ABSTRACT

MITIGATING ALKALI SILICATE REACTION IN RECYCLED CONCRETE

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The objective of this study was to investigate the reactivity of concrete containing recycled concrete aggregates (RCA) that had shown distress due to alkali silicate reaction (ASR) prior to being recycled. This study evaluated several mitigation techniques to control ASR in concrete containing RCA. RCA was studied to investigate expansion characteristics during early age hydration. The development of mitigation guidelines and information on the behavior of concrete containing RCA are important issues as natural aggregate supplies dwindle and alternative aggregate sources become necessary.

Mitigation work was done with three different aggregate types; an igneous fine-grained quartzite blue rock, as presently quarried, RCA blue rock, and limestone. The natural blue rock aggregate concrete was used as a control. Concrete's containing limestone was used to investigate the reactive characteristics of the fine aggregate and the behavioral differences of the cements used. The mitigation strategies include the use of low alkali cement, class F fly ash, ground granulated blast furnace slag (GGBFS), lithium nitrate, and silica fume blended cement. These materials were incorporated into concrete mixtures by cement substitution and direct application.

Concrete mortar-bars, prism beams, cubes and cylinders were used to investigate the mitigation strategies. ASTM C 1260, ASTM C 1293, and modified versions of these tests were used to evaluate expansion caused by ASR.

Low alkali cement, class F fly ash, ground granulated blast furnace slag, and lithium nitrate showed potential in controlling ASR distress in natural aggregate concrete and RCA concrete. In general, RCA concretes showed larger expansion rates than natural aggregate concretes. RCA is a viable aggregate source in new portland cement concrete mixtures when ASR mitigation strategies are properly applied.

CHAPTER 1

INTRODUCTION

INTRODUCTION

Alkali silicate reaction (ASR) distress in concrete structures has been observed in the United States since before 1940.[1] Thomas E. Stanton reported concrete pavement failure in early 1938 on a section of concrete pavement north of Bradley in the Salinas Valley, Monterey County, California. Failure was attributed to coarse and fine aggregates used in the portland cement concrete (PCC). The concrete distress led to excessive cracking throughout the length of concrete slabs and buckling at expansion joints. This diagnosis of ASR has prompted numerous reports of concrete deterioration that show ASR to be at least one of the leading causes of distress in structures located in humid environments.[2]

Much of the concrete infrastructure in the United States is inadequate and in need of rehabilitation or even reconstruction. The construction of the interstate highway system in the United States began in the 1950's and as many roadways are constructed with 50 year life expectancies the roadways are starting to become obsolete and in need of major rehabilitation or replacement. It will cost trillions of dollars to complete this rebuilding process. Problems with ASR distress and concrete durability, seen throughout the country, are direct results of reactive aggregates being used in concrete structures. Although non-reactive aggregates do exist in this country, they are often located in remote locations and are very expensive to transport in large quantities. A viable alternative to this aggregate problem is recycling waste concrete. This not only reduces construction and demolition waste, but it also gives a potential aggregate source for new concrete.

Recycling waste concrete has been done in European countries since the end of world war two. Recycling concrete waste is a large part of the aggregate industry in present-day practice. Little is known about recycling concrete that has undergone ASR distress. Although the use of RCA in new concretes has not been popular, there is a need to understand the behavior of ASR distressed RCA in new concrete environments. For example, the recycling of construction and demolition waste as aggregates is well underway in Belgium with RCA representing 10% of the national market of aggregates.[3] With a decreasing supply of natural aggregates, the aggregate industry will be forced to find other materials to satisfy the ongoing demand for construction materials.

Although recycled aggregate concrete has not gained popularity in present day construction, many concrete roadway projects have been done using recycling techniques. Iowa rebuilt U.S. Route 75 in 1976 with recycled coarse and fine aggregates in new concrete mixtures. The project was successful using the old roadway for coarse aggregate and a mixture of recycled fine material with 15% concrete sand to give the concrete a higher workability. With this successful project, the state of Iowa undertook two more roadway projects incorporating recycled aggregates. More recent projects were done in Minnesota when a recycling project was conducted on U.S. 59 in the southeastern part of the state in 1980. This project incorporated recycled material that had undergone D-cracking as a major distress. The new pavement showed promising results with a durable product.[4] Other states have used RCA in new concrete, such as MN, WY, MI, ID, TE, in the past, but only as unbound base material.[4]

Information on projects incorporating recycled aggregate that has undergone ASR is very limited. Limited research has been done with RCA having undergone ASR, but it is recommended that recycled aggregate be tested for ASR prior to its use. It is important to know if the ASR of the RCA has the potential to continue or reactivate if the distressed concrete is recycled. Past recommendations included the use of the ASTM C 227 test with various alkali contents to determine what level of alkali is acceptable for the recycled material to start showing ASR expansive behavior in new concretes.[4] New testing procedures are presently being used to evaluate the potential for ASR distress with aggregate sources and concrete specimens.

Recent publications show that proper mitigation procedures can control or eliminate destructive ASR in PCC.[5] Accepted mitigation materials include low alkali cement, class F fly ash, ground granulated blast furnace slag (GGBFS), metakaolin, lithium nitrate, and silica fume. Mitigation materials are commonly used in natural aggregate concretes as a means to make a high quality product material and to use these materials, especially class F fly ash, that would otherwise be land filled, and GGBFS in a productive way.

PROJECT OBJECTIVES

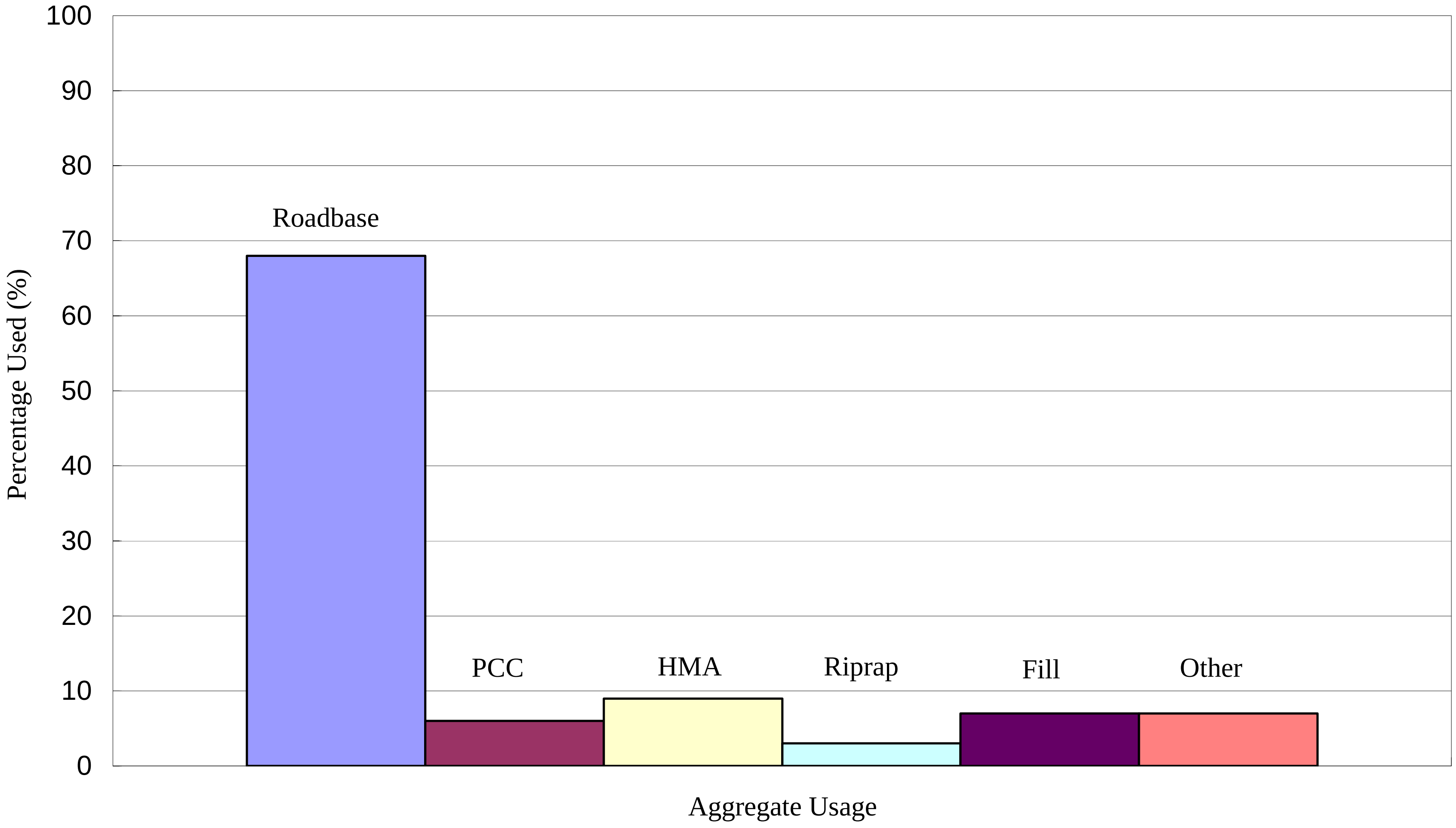
The main goal of this research project was to investigate the ability of presently accepted ASR mitigation techniques to control ASR in concrete made with ASR distressed RCA. Existing ASR potential testing methods were used to evaluate their applicability with concretes containing RCA. The result of this project was the development of ASR mitigation strategies to control ASR distress with concrete containing ASR distressed RCA. This information is useful as natural aggregate supplies are decreasing and new material resources are necessary for the future production of PCC.

RECYCLED CONCRETE AGGREGATE (RCA)

Recycling waste concrete became a reality in Europe after the end of world war two.[6] Cities faced the challenge to rebuild infrastructure and deal with large amounts of demolition debris. RCA has gained popularity as roadbase material, erosion control (riprap) material, and general fill throughout the United States and Internationally. Many state department of transportation agencies (DOT's) have adopted the use of RCA as an acceptable natural aggregate substitution in new concrete and in asphalt concrete pavements.[6] RCA use breakdown shows 68% used as roadbase material, 6% in new PCC mixtures, 9% in hot mix asphalt (HMA), 3% for high value riprap, 7% for general fill and 7% in other uses.[7] Figure 1-1 illustrates this material breakdown of RCA in present-day construction practice.

There is not a tremendous amount of information known about ASR distressed RCA in new concrete. Past studies have shown RCA concretes show comparable characteristics to regular concrete mixtures with minor differences. Compressive strengths were lower for RCA concretes, the specific gravity of the RCA was lower than natural aggregate, and more water and cement was needed in RCA concrete to compensate for absorption and angularity in the RCA. The major differences between RCA and natural aggregates are that RCA has a larger absorptive percentage and a lower specific gravity.[6,8]

Figure 1-1: Recycled Aggregate Usage



Past projects have shown RCA is an acceptable aggregate source in new concrete. In general it was found that the use of recycled fine material can cause poor workability characteristics. This can be corrected with the substitution of natural concrete sand or the addition of more water and cement to keep the water-to-cement ratio constant for the mixture. It was found that less air-entraining admixture was needed with recycled aggregate concretes than with natural aggregate concrete to reach desired air content. Connected with this observation was the increased freeze-thaw resistance of recycled aggregate concrete compared to natural aggregate concrete when equivalent air-entrainment dosages were applied.[4,6] Recycled aggregate, containing aggregate and paste fractions, contain a large amount of void space from the paste portion of the material. This provides more voids in the concrete for freeze/thaw distress relief. The paste percentage associated with the recycled aggregate is an important characteristic of the material and this can be changed with repeated crushing cycles during the recycling process of the material.[4] Along with recycled aggregate and natural aggregate concrete mixture comparisons, the aggregate sources must independently be compared for quality assurance in meeting concrete specifications. Table 1-1 shows comparative data between RCA and natural aggregate sources.

Table 1-1: RCA and Natural Aggregate Comparisons[9]

	Recycled Aggregates	Natural Aggregates
Sources of material	Scrap concrete and scrap asphalt pavement.	Sand and gravel and crushed stone deposits.
Use	Generally lower value applications such as road base and asphalt concrete.	Wide range of construction uses; primarily as portland cement concrete, road base and asphalt concrete.
Cost to Produce	Capital: $4-$8/ton Operating: $2.50-$6/ton Tipping fee credit: $1.10/ton (Cost generally comparable to natural aggregates).	Production costs benefit from economics of scale. Mining, environmental control and transportation costs add to cost.
Incentives for production	Reduces amount of material in landfills, slows natural aggregate depletion, limits environmental disturbance, lower transportation and disposal costs for large projects.	High local aggregate demand, local resources meet quality specifications for wide range of markets, resources currently abundant, production and transportation costs relatively low.
Deterrents for Industry	Requires abundant feed supply, favorable transportation/tipping fees structures and proper site design. High capital requirements, variable quality requires monitoring, limited demand and price control and often a seasonal industry.	Land use/zoning issues may restrict resource development, decreasing quality, increasing environmental regulations and transportation requirements.
Major Industry Issues	Recycling issues must be weighed against competing land issues, development issue and societal pressures. Recycling works best in urban areas with infrastructure replacement, limited natural aggregate resources, high disposal costs and strict environmental regulations.	Land use development issues make resource acquisition more difficult, expensive, and time consuming. Decrease in gravel/sand ratio requires addition of mountain gravel, increasing transport distances, cost, and road wear. Increased regulation, competition and substitution concern industry.

It can be seen that RCA is a competitive alternative to natural aggregates and this is positive information with the aggregate industry facing shortages of naturally occurring raw materials. Aggregate suppliers throughout the continental United States are facing increased supply demands with decreasing raw materials available. Aggregate supply sites are moving into isolated areas and with the recent increase in fuel this will cause prices to go up because forty-five percent of the cost of aggregates is in their transportation.[10]

RCA has been used in new concrete pavements, but natural aggregates are the preferred choice of state and private organizations to ensure a quality product. Figure 1-2 shows recycled aggregate from a concrete roadway slab.

Figure 1-2: Recycled Aggregate Sample from a Concrete Slab

With diminishing supplies of natural aggregates available, the aggregate industry looks for other options to keep a steady material demand replenished. Large amounts of demolished PCC from roadways, buildings, and maintenance projects are available as the

United States infrastructure is rehabilitated. The United States interstate highway system was constructed in the 1950, 60 and 70's and much is in need of extensive repair, rehabilitation, or replacement. PCC recycling is most productive in urban areas where replacement of infrastructure is occurring, natural aggregate sources are limited, disposal costs are high and strict environmental regulations prevent disposal.[11]

ALKALI SILICATE REACTION (ASR)

ASR is a universally accepted concrete distress mechanism that was first observed in the United States in 1938. In order for the reaction to occur four ingredients must be present in a concrete structure; reactive aggregate, alkali, calcium, and water. ASR does not occur in all concrete structures built, but in most cases all of these previously mentioned materials are present. ASR can take as little as months or as long as decades to mature and cause cracking that extends to the outside surface of a concrete structure. This is a function the material in the PCC mixture and the surrounding environment the structure is subjected to. No published cases have been found where ASR was the cause of a structural collapse, but it should be noted that ASR will open a PCC structure up to further deterioration by freeze/thaw mechanism, deicing salt intrusion (steel corrosion), or chloride intrusion in marine environments.[12] ASR has been controlled using various mitigation strategies that have reduced the expansive characteristics common with the reaction. The following outlines the mechanism, which drives ASR in a concrete structure.[13]

(1) Development of high concentrations of alkali hydroxides in the pore solution.
(2) Reaction with silica from aggregate and the formation of reaction product gel.
(3) Expansion arising from fluid flow into the gel.

(4) Cracking and subsequent deterioration.

Figure 1-3 shows a polished concrete sample with ASR gel in and around aggregates and hydrated cement matrix.

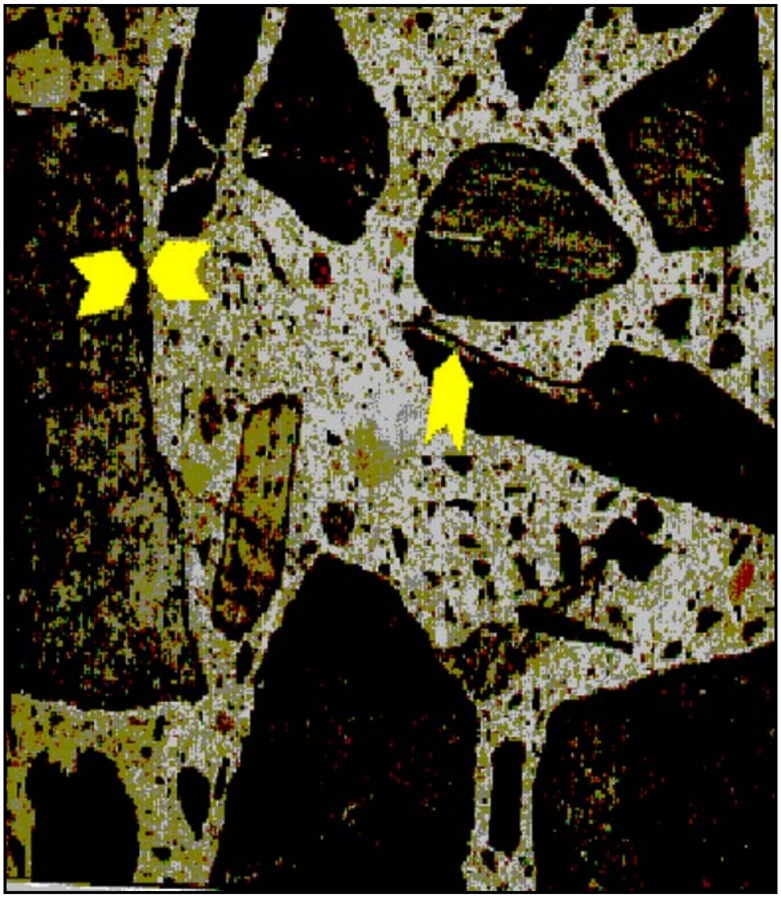


Figure 1-3: Polished Concrete Sample with ASR Gel

Reactive Aggregates

Amorphous, or soluble, silica is the material associated with an ASR reactive aggregate. All aggregates contain silica (SiO_2), but reactive aggregates have a poor crystalline structure. This poor crystalline structure results in an aggregate with poor bonding characteristics that is easily broken down by high pH pore fluid in concrete. The aggregate surface is attacked and amorphous silica both dissolves and combines with calcium to form ASR gel. The use of non-reactive aggregates, both coarse and fine, is the only definite way to stop ASR from occurring in a PCC structure.

Opal, obsidian, cristobalite, tridymite, chalcedony, cherts, cyptocrystalline volcanic rocks (andesites and rhyolites) and strained metamorphic quartz are alkali reactive and show poor resistance to alkaline solution attack. Feldspars, pyroxenes, amphiliboles, micas, and quartz, all minerals incorporated into granites, gneisses, schists, sandstones and basalts are classified as innocuous minerals found in reactive aggregates.[2]

Alkali

The major contributor of alkali in concrete originates from the cement in the mixture. Na_2O and K_2O provide alkaline hydroxides in the pore water solution of the concrete. This causes a high pH, 12.5 or higher, a high concentration of hydroxyl ions in the concrete pore solution. Contact between this high pH pore solution and ASR reactive aggregates cause the dissolution of amorphous silica material and leads to the formation of ASR gel. The total alkali content, expressed as $Na_2O_{equivalent}$ ($Na_2O + 0.658K_2O$), of the cementious material directly effects the hydroxyl concentration of a concretes pore solution. High alkali cement results in a harsher environment for ASR distress to occur.

Average alkali contents in portland cements have increased since the 1950's and now contain up to 0.80% Na_2O_{eq} on average.[14] The rise in alkali content of cements was a direct result of the clean air act passed in 1990.[15] Kiln gases, containing alkali and sulfur, were no longer allowed to be openly vented into the environment. Vented kiln gases have strict restrictions that must be met. Recycling kiln gases back through a cement plant puts alkali back into the system and increases total alkali levels of the final cement product. Another source of alkali in cement comes from the ingredients that a particular plant may use. This will vary for cement plants in different geographical locations. Transportation of cements, like aggregates, is expensive and construction practices will use what product is abundant in an area.

A total alkali content of 0.60% in a cement has been published as a control level to control ASR distress with reactive aggregates.[15] This alkali level is not able to produce a high enough hydroxyl ion concentration within the concrete pore solution to break down amorphous silica in reactive aggregates.

Calcium

It is universally accepted that the presence of calcium ions (Ca^{+2}) are necessary for ASR to occur.[13] It is not agreed upon whether ASR gel can form without the presence of calcium ions or vise versa.[1,16] In a study done by Chatterji it was stated that the presence of calcium hydroxide is essential to the ASR process, and that systems lacking calcium hydroxide simply do not undergo ASR distress.[17] ASR gel that has formed in a concrete system may not show expansive characteristics if ample calcium ions are not available.

Water

The presence of water in concrete may be from mix water or outside sources; including rainfall or surface runoff. The role of water in ASR is to make the ASR gel swell by osmotic intake of fluid.[13] ASR gel by itself is not an expansive material, but when outside moisture is present it swells and causes internal pressure within the concrete system. The presence of water also causes a relative humidity environment in a concrete system that must exceed eighty-five percent for favorable ASR conditions.[16] The increased relative humidity level provides a situation within a concrete structure where external water is available to ASR gel for the swelling mechanism.

These four materials must be present within a concrete structure for ASR to occur. The absence or shortage of a material would prevent the reaction from starting or stop ASR that had started.

MITIGATION PROCEDURES

It has been shown that mitigation strategies can control ASR distress when applied to new concrete mixtures in the correct dosages. Low alkali cement, Class F fly ash, GGBFS, metakaolin, lithium nitrate, and silica fume are all proven mitigation strategies with concretes that utilize natural aggregate sources.[5] Information on these mitigation strategies ability to control ASR distress with ASR distressed RCA has been limited and inconclusive. This topic was addressed and studied in detail throughout this research project.

RCA: A NEW AGGREGATE SOURCE

The physical and chemical makeup of RCA needs to be understood before it can be used in new concrete. There are two possibilities when using RCA as a new aggregate source in concrete. The RCA can come from concrete that has shown signs of ASR distress or concrete that has not. If concrete has shown ASR distress the reaction may be complete or partially complete. This information must be understood when RCA concrete production occurs. A RCA coming from concrete that has completely reacted may never show any signs of ASR distress when put into new concrete. This situation would show that all available amorphous silica from the original aggregate source had been used as ASR occurred while the PCC was in service or that the new concrete environment does not promote ASR distress. A RCA coming from concrete that has partially reacted may show immediate ASR distress when put into new concrete. If the pH of an in-place concrete had dropped to a level such that ASR could not be supported it could reactivate when the RCA was batched into a new mixture as the pH would be elevated. If concrete has shown no ASR distress in the field, the process of recycling and incorporating the RCA into new concrete may trigger the reaction when a more aggressive environment is introduced. The alkali present in the reacted ASR gel, contained within the RCA, can have a detrimental effect on these new concretes. This internal alkali may have the ability to reactivate and contribute significantly to ASR distress in RCA concrete. The alkali from cement and RCA in concrete can cause very high initial pH levels that are more aggressive than those seen in concrete where cement is the only alkali source. Early ASR distress in concrete structures can lead to premature loss of serviceability and structural integrity issues.

STANDARDIZED ASR TESTING

This research incorporated two ASR testing specifications published within ASTM standards volumes. It was necessary to test aggregate and full-scale concrete potential for ASR distress. ASTM C 1260 was used to investigate the individual properties of aggregates used in this research.[18] This test shows results of an aggregates potential to be ASR reactive. Along with information on reactive aggregate sources used in concrete mixtures, it is necessary to understand the behavior of the PCC mixture as a whole, not just the individual components of the mixture. To investigate this information ASTM C 1293 was used.[19] This test takes into consideration all ingredients present in the concrete. When used together these two testing procedures can give good indication of the expected aggregates field performance.[20, 21]

Testing Modifications

Both the ASTM C 1260 and 1293 testing procedures were modified so that recycled aggregate concrete samples could be evaluated with rapid testing procedures and to shorten the testing duration for the ASTM C 1293 testing procedure. The modifications included varying sample dimensions, introducing electrical current to concrete samples and providing different moisture and temperature environments for testing conditions.

CHAPTER 2

MATERIALS

INTRODUCTION

This research investigated the use of ASR distressed RCA as an alternative to natural aggregate in new concrete. RCA concrete mixes were investigated for susceptibility to the reoccurrence of ASR. Aggregate sources used in this research were ASR reactive. Control cement was high in equivalent alkali, able to create an aggressive concrete pore solution. This ensured ASR reactivity in PCC samples made for investigation with presently used ASR mitigation strategies. ASR mitigation strategies evaluated to see if they were effective when used with RCA. Only ASR mitigation strategies showing promising results in controlling ASR distress with natural aggregate concrete were considered.

MATERIALS

Aggregates

Three aggregate sources were used in this research work. Blue rock, a quartzite aggregate from Westbrook, Maine was used as a control aggregate. A recycled concrete from Interstate I-95 near Gardner, Maine, that incorporated blue rock aggregate and a non-reactive limestone from South Wallingford, Vermont. The blue rock aggregate, in both sources, had identical mineralogical characteristics. The blue rock aggregate originating from Maine has been previously characterized as ASR reactive.[22] The recycled PCC showed signs of ASR distress in the field before removal.

The control, blue rock, used in this study was characterized as being from the Berwick Formation (DSb) in the Maine Geological Survey.[23] The principle part of this rock formation consists of thin-to-medium bedded, occasionally massive, biotite quartzite and quartz-biotite schist containing variable amounts of plagioclase. Locally embedded with these rock types is quartz-biotite-muscovite schist with very rare garnet and staurolite.[23] This rock type is characterized as potentially ASR reactive having a 14-day expansion of 0.17% using the ASTM C 1260 mortar-bar test.[18] A 14-day expansion less than 0.10% characterizes an aggregate as non-reactive, a 14-day expansion between 0.10% and 0.20% characterizes an aggregate as potentially reactive and an expansion greater than 0.20% characterizes an aggregate as reactive for the ASTM C 1260 mortar-bar test. The Maine Department of Transportation has done ASR testing on aggregates throughout the state and their results showed the Westbrook blue rock at a 14-day expansion of 0.327%, indicating the aggregate is reactive with expansion greater than 0.20%.[22] Both ASTM C 1260 mortar-bar results show the aggregate to have reactive characteristics with expansion greater than 0.10% and most likely vary due to variation within the quarry.

The RCA blue rock material had undergone deterioration that caused rehabilitation work on Interstate I-95 in Gardner, Maine. The origin of the blue rock coarse aggregate in the RCA blue rock was the same as the natural blue rock, differing in time and location that they were taken from the aggregate quarry. ASTM C 1260 mortar-bar testing was done on the recycled blue rock aggregate, by removing it from the RCA through an accelerated aging procedure of extreme heating and cooling cycles.[24] A 14-day expansion of 0.16% in the ASTM C 1260 mortar-bar test was recorded, indicating the material was potentially ASR reactive. The aggregate sources were also tested for their absorption characteristics. The blue rock RCA showed 4.10% absorption, almost ten times that of natural blue rock at 0.47%.

The natural blue rock and RCA blue rock ASTM C 1260 mortar-bar samples were made with cement having a total alkali content of 1.31%. Figure 2-1 shows the ASTM C 1260 mortar-bar results for the natural blue rock and RCA blue rock testing. All graphs in this research incorporate three test samples for each graphed line, consistent with ASTM testing standards. Both aggregates show potentially reactive characteristics having percent expansions between 0.10 % and 0.20% at 14-days.

South Wallingford limestone was used as a control aggregate to show if materials other than coarse aggregate would contribute to ASR distress. Figure 2-2 shows the ASTM C 1260 mortar-bar results for the limestone aggregate with a 14-day expansion less than 0.10%, thus showing non-reactive ASR characteristics. ASTM C 1260 mortar-bar results were well below detectable limits, showing 0.019% expansion with control cement and 0.005% expansion with low alkali cement. The low alkali cement had a total alkali content of 0.26%.

Fine aggregate used in the test concrete mixes was non-reactive glacial sand from Ossipee Aggregates Corporation in Ossipee, New Hampshire. The New Hampshire Department of Transportation (NHDOT) has performed ASTM C 1260 mortar-bar testing on this fine aggregate and found a 14-day expansion of 0.038%, well below potentially reactive limits.[25]

An aggregate material overview is presented in table 2-1, which contains individual characteristics needed for mix proportioning.

Table 2-1: Aggregate Material Characteristics

Aggregate	**Specific Gravity (Gs)**	**% Absorption**	**DRUW (lb/ft3)**	**Fineness Modulus**
Natural Blue Rock	2.69	0.47	96.76	-
RCA Blue Rock	2.35	4.10	79.96	-
Limestone	2.74	0.50	103.4	-
Sand	2.75	1.13	-	2.68

Note: DRUW or Dry Rodded Unit Weight

The dry rodded unit weight of the RCA blue rock is due to the paste fraction of the RCA.

Total and soluble alkali testing was done on the natural blue rock and recycled blue rock aggregate to investigate alkali addition from either aggregate source when incorporated into a concrete mixture. It was found that natural blue rock aggregate contained 3.98% total alkali, while recycled blue rock contained 3.83% total alkali. Soluble alkali testing results showed the blue rock RCA is capable of contributing a larger amount of alkali to a concrete mixture than the natural aggregate. The soluble alkali content of the blue rock RCA aggregate was 0.11% and the natural blue rock was 0.012%. The recycled blue rock aggregate showed over nine times the soluble alkali content when compared to the natural blue rock aggregate. Alkali is released from portland cement and directly affects the increase of the hydroxyl ion content of the concrete pore solution. Alkali contribution from aggregate sources has been shown to cause an increase in ASR reactivity of a concrete.[26] The high soluble alkali of the RCA blue rock was attributed to the paste fraction of the aggregate.

Figure 2-1: Expansion versus time for ASTM C 1260 (natural blue rock and RCA)

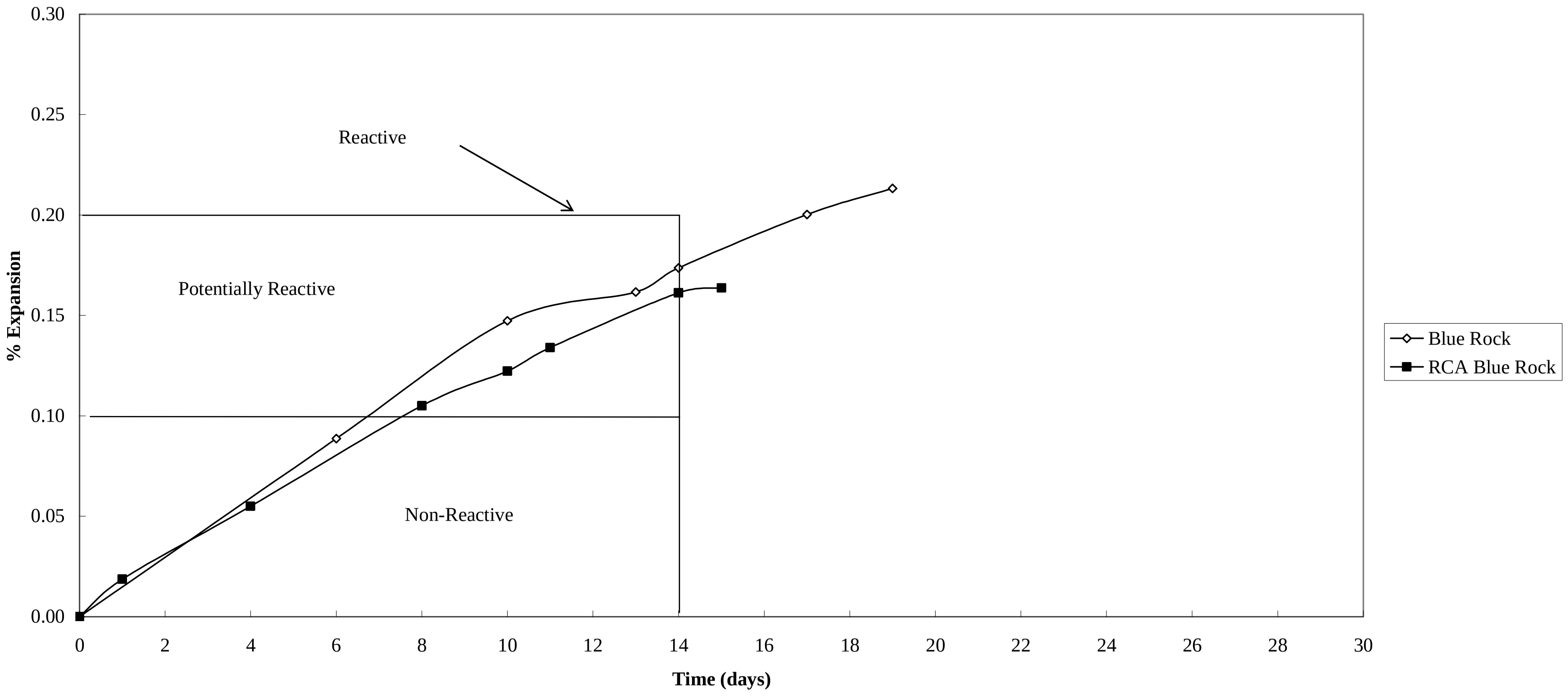
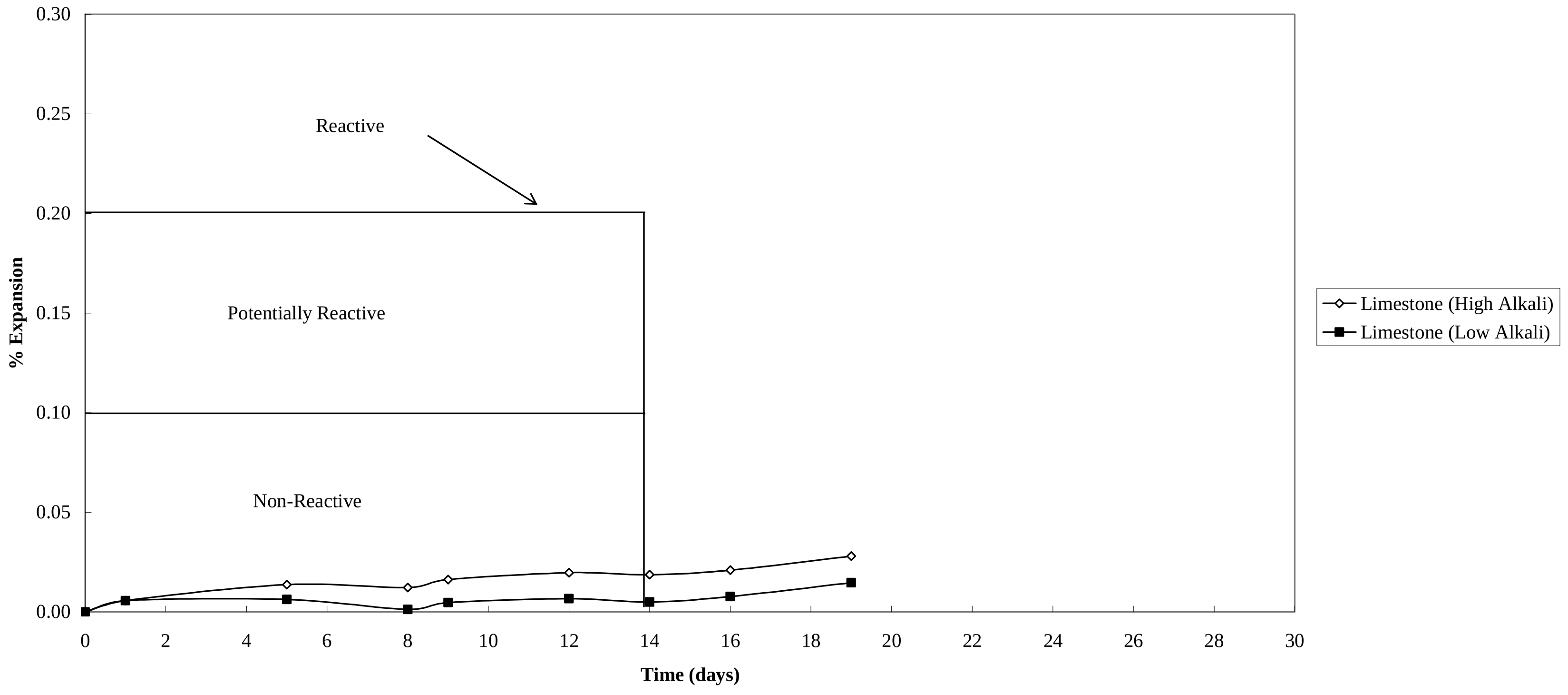


Figure 2-2: Expansion versus time for ASTM C 1260 (limestone)



Cementitious and Mitigation Material

The control type II portland cement that was used had an equivalent alkali content of 1.31% (Na_2O = 0.45% and K_2O = 1.31%). This cement was used to induce ASR in concrete samples in order to test accepted mitigation strategies in extreme conditions.

Mitigation strategies; low alkali cement, class F fly ash, GGBFS, lithium nitrate and silica fume blended cement were evaluated in this study. Class F fly ash was substituted at 15% and 25%, while GGBFS was substituted at 25% and 55% with the control cement. Lithium nitrate was used at a 100% dosage. The quantity of lithium nitrate required to suppress deleterious ASR expansion has been shown to depend primarily on the quantity of equivalent alkali in the concrete, mostly supplied from the cement as sodium and potassium. A molar ratio of [Li]/[Na+K] > 0.74 has been found to be sufficient to control ASR distress with most aggregates.[27] This molar ratio is equivalent to 0.55 gallons lithium nitrate per pound of equivalent alkali in the PCC mixture.

Overviews of all properties for individual cements used in this study are presented in table 2-2.

Table 2-2: Cement Material Characteristics

Material	**Specific Gravity (Gs)**	**Na_2Oeq (%)**	**MgO (%)**	**Autoclave Expansion (%)**	**CaO (%)**	**Loss on Ignition (%)**
Control Cement	3.15	1.31	3.1	0.13	61.8	1.37
Low Alkali Cement	3.15	0.26	1.1	0.09	NA	1.4
Silica Fume Cement (8%)	2.75	0.95	2.7	0.07	58.5	0.9

Overviews for properties of class F fly ash and GGBFS used in this study are presented in table 2-3.

Table 2-3: Class F Fly Ash and GGBFS Material Characteristics

Material	**Specific Gravity (G_s)**	**Na_2Oeq (%)**	**CaO (%)**
Class F fly ash	2.22	0.81	1.46
GGBFS	2.85	0.41	NA

Complete chemical and physical data for the cements and class F fly ash are available in the appendix A.

The lithium nitrate admixture, Lifetime™, is a product of FMC Corporation in Bessemer, North Carolina.

All concrete test mixes were proportioned with a water-cement ratio of 0.45, an air content of 6%, a cement content of 708 lb/yd^3 and a maximum aggregate size of 0.75 inches. WR Grace Darex II, the air-entraining admixture, was used to target the air at 6%. Coarse and fine aggregate contents varied between natural blue rock aggregate and RCA blue rock so as to keep cement content, water-cement ration, and batch yields constant. RCA blue rock had a lower dry-rodded unit weight, a lower specific gravity and a higher absorption capacity than natural blue rock aggregate.[4,6] A volume of course aggregate per unit of volume of concrete factor of 0.63 was used to proportion all test mixes. The RCA blue rock aggregate was stored in sealed containers and purged with nitrogen to minimize carbonation. All other materials were stored in low humidity sealed containers at room temperature in the materials laboratory facility.

Limited information was available about the PCC mixture that produced the recycled aggregate used in the study. Michael J. Redmond of the Maine Department of Transportation gave information on the original PCC mixture, characterizing it as a "class

A mix".[28] Table 2-4 shows comparisons between the original PCC mixture and that used in this study.

Table 2-4: PCC Mix Proportions for Original RCA Concrete and Research Concrete

Concrete Mixture:	**RCA PCC Mixture (Original)**	**PCC Mixture (Present Research)**
Cement Content:	+/- 600 lb/yd^3	708 lb/yd^3
Water-Cement Ratio (W/C):	0.40 - 0.45	0.45
Air entrainment Content:	6 %	6 %
Maximum Aggregate Size:	1-1/2 inches	0.75 inches

Mixture comparisons show a smaller amount of cement used with the RCA concrete mixture and a larger aggregate size. Knowing the original concrete mix design and where the RCA material originated was useful to predict levels of alkali that could potentially be leached into new concrete mixtures made with the RCA blue rock material.

MITIGATION MATERIALS

Low alkali cement, class F fly ash, GGBFS, lithium nitrate and silica fume blended cement were used as mitigation strategies in this research. Low alkali and/or blended cements, a minimum of 25% Class F fly ash, 40-50% GGBFS, 100% lithium nitrate dosages and 5-10% silica fume cement replacement are accepted mitigation levels according to the Naval Facilities Engineering Command in the Alkali-Silica Reaction Mitigation: State-of-the-Art report.[5]

Low Alkali Cement

Low alkali cement has been characterized as one that contains less than 0.6% total alkali or Na_2O_{eq}.[16] This alkali content has been shown to control most deleterious ASR expansion with ASR reactive aggregates. The main drawback to low alkali cement has been the elevated cost of the material when compared to higher alkali cements. Past research has shown low alkali cements control ASR distress with no other mitigation strategies necessary.[5] Limiting the alkali content from portland cement keeps the hydroxyl ion content of the concrete pore solution below a threshold level required to dissolve amorphous silica in reactive aggregates and form ASR gel. Low alkali cement increases the durability of recycled aggregate concrete against ASR distress.[3]

Class F Fly Ash

Fly ash is the product of coal-fired power stations and the most common artificial pozzolan. Class F fly ash is mainly siliceous, not having hydraulic properties characteristic with portland cement. Fly ash reacts with calcium hydroxide ($Ca(OH)_2$) and water to produce calcium-silicate-hydrate (CSH), the most durable hydration product of concrete. This fly ash reaction takes extra time because the portland cement must first hydrate and therefore produce $Ca(OH)_2$, which then reacts with the fly ash. When pH levels reach 13.2 +/- fly ash particles break down and enter into the capillary pore system of a concrete matrix.[29] With this a pozzolonic reaction with water and $Ca(OH)_2$ forms CSH and a reduction in the capillary porosity of the system occurs. This causes a reduction in the available alkali because some of the alkali is chemically captured in the CSH.[29]

The overall benefit of using class F fly ash in concrete is a more durable product. Reduced hydroxyl ion concentrations lower the risk of ASR and increased impermeability keeps water out of the concrete matrix to stop ASR gel from swelling. Reduced permeability of the concrete is due to the increased microscopic density of the concrete. Fly ash increases workability to fresh concrete and reduces the amount of water needed for a concrete mixture.[30]

Many studies have shown that class F fly ash is beneficial to prevent the deleterious effects of ASR. Some have gone as far to say that fly ash should be the fourth ingredient in a high quality concrete mixture.[31] The long term effects of class F fly ash with twenty-five percent cement mass substitution has shown the ability to control ASR distress when used with reactive aggregates and high alkali cements with up to 1.38% total alkali contents.[32] Class F fly ash is a proven ASR mitigation strategy which not only controls deleterious expansions, but also creates a high quality concrete resistant to other chemical and physical attack.

Ground Granulated Blast Furnace Slag (GGBFS)

GGBFS is produced by pulverizing molten slag that has been quenched by water or another cooling process from the production of iron. GGBFS is not a pozzolan, but has hydraulic properties when in contact with water. The reactivity of GGBFS is dependant on its composition, glass content and particle size.

GGBFS has shown many beneficial uses with PCC. It provides increased workability with fresh concrete as well as decreasing heat of hydration temperatures to protect against thermal cracking distress. Substituting GGBFS with portland cement provides a denser microstructure within the hydrated cement paste, which improves long-term strength, durability and decreased permeability of the concrete. It has also been shown that the risk of ASR can be eliminated when GGBFS is substituted into PCC.[16] GGBFS has been shown to increase the durability of recycled aggregate concrete against ASR distress.[3] The beneficial aspects of GGBFS are directly related to the percentage used in a concrete mixture.

GGBFS has been used in PCC for over a century. Blending GGBFS with portland cement results in a concrete with a denser microstructure of hydrated cement paste than a straight PCC mixture. This provides a reduced permeability by a factor of one-hundred compared to a concrete that does not incorporate GGBFS.[33] The dense microstructure provides a low penetrability for external substances to enter the concrete; including water, deicing salts and chloride ions. This low penetrability characteristic is very beneficial in controlling ASR distress. The dense hydrated cement paste microstructure also decreases the mobility of alkali in the concrete, making it more difficult for high hydroxyl ion concentrated pore solution to attack ASR reactive aggregates. Fifty percent GGBFS replacement levels of portland cement have shown positive results combating ASR distress in many structures when compared to other concretes not incorporating GGBFS.[5,33]

In a direct comparison between a concrete spillway made with GGBFS and a concrete bridge with no GGBFS, it was shown that in a ten year period the spillway showed no ASR distress, while the bridge had significant map cracking damage, a characteristic cracking pattern associated with ASR.[33] The use of GGBFS provides superior durability qualities to a concrete compared to a standard PCC mixture.[16]

Lithium Nitrate (Lifetime™)

The mechanism used for lithium nitrate to suppress ASR distress is not well understood. The general understanding is that lithium is incorporated into ASR gel to produce a non-expansive product when put into contact with moisture. As a result, the ASR gel becomes an innocuous product and deleterious expansions do not occur. Lithium is also a member of the alkali family and is more electropositive than sodium and potassium, therefore having a greater affinity for silica. Pore solution studies show that lithium is absorbed by CSH and ASR gel, resulting in a non-expansive product. Lithium nitrate is dosed into concrete based on the equivalent alkali content of the mixture.[34]

Past studies show lithium will eliminate ASR expansion when used properly. Lithium nitrate, unlike other lithium containing compounds, shows no pessimum effects when intermediate dosages are used.[34] Research data show lithium containing compounds control ASR expansion with ASR reactive aggeragtes.[35]

Silica Fume

Condensed silica fume or microsilica is the byproduct of silicon and ferrosilicon alloys from high-purity quartz and coal in submerged-arc electric furnaces. Gaseous silica oxidizes and condenses in the form of extremely fine spherical particles of amorphous silica (SiO_2), creating silica fume. It is a highly reactive material and its small particle size increases the reaction time with $Ca(OH)_2$ produced by the hydration of portland cement. Being a pozzolan, silica fume reacts with $Ca(OH)_2$ and water to produce CSH and produce a denser, more durable hydrated cement paste matrix.

Silica fume is beneficial as a PCC additive in many ways. Its small particle size allows it to fill spaces around and between cement particles and improve packing within the cement paste matrix and after reacting it improves low-permeability characteristics of the concrete. Bleeding characteristics of the concrete decrease with silica fume and mixture cohesion is improved. Silica fume is commonly used with high strength concrete bridge deck mixtures as it provides high early strengths in concrete and low permeability characteristics to control deleterious chloride ion penetration to reinforcing steel. The small particle size makes for close interactions with aggregates and cement paste at transition zones. The transition zone will have a lower porosity with the use of silica fume and therefore a higher strength.[16]

Research shows that silica fume must be substituted into a concrete mixture at a minimum five percent by mass of portland cement to be effective, this provides enough silica fume to cover the surface of aggregate particles.[16] Silica fume creates durable PCC with decreased permeability, which stops the ingress of external substances that may cause distress problems. Silica fume reduces the alkali content of the concrete pore fluid, reducing the pH and therefore stops ASR if hydroxyl ion concentrations are not high enough to dissolve amorphous silica in reactive aggregates. The dense hydrated cement paste will also slow the migration of the high alkali pore solution through the concrete matrix system and slow the ingress of water into the concrete with decreased permeability characteristics of the concrete.[16]

In Iceland, the use of silica fume for the past twenty years has virtually eliminated ASR when used in concrete structures.[36] Silica fume addition to any concrete is beneficial for high early strength, decreased permeability, durability and to decrease the alkali content of concrete pore solution.

CHAPTER 3

METHODS

INTRODUCTION

This research investigated the ASR expansive characteristics of different concrete mixtures. ASTM testing procedures were followed for preparation of concrete mixtures, mixing, curing, demolding and determining length change of the concrete samples. To study individual properties of materials used in this study a variety of tests were conducted using ASTM, AASHTO and other independent testing procedures. All testing procedures were followed to gather and understand ASR expansive data and ultimately configure a mitigation strategy to control ASR distress in RCA concrete.

TESTING OVERVIEW

Various concrete specimen testing environments and sample sizes were tested to determine if concretes showed ASR reactivity characteristics and how quickly these results could be gained. New testing procedures need to show good correlation to accepted ASTM test results in terms of when concrete samples pass and fail ASR expansion limits. The two main tests used in this study are published in the annual book of ASTM standards, which were further adjusted to test recycled aggregate concrete samples in a rapid testing environment and to shorten the testing duration time for the standard tests. The goal was to create new testing procedures to predict ASR distress in concrete in a shorter duration than presently accepted ASTM specifications. The standard tests were modified by changing test sample size, testing environments and moisture conditions. These testing procedures were developed from earlier work done at the University of New Hampshire.[25]

LABORATORY PROCESS

Specimen Preparation

The concrete to be used as recycled aggregate required crushing concrete road slabs to acceptable aggregate grading. The concrete slabs were initially broken apart with a fifteen-pound sledgehammer and a rotary hammer drill. The resulting particles were run through a jaw crusher that produced aggregate sizes of one inch plus to dust particles as shown in Figure 3-1.

Figure 3-1: Jaw Crushing Machine

The resulting aggregate was seived and the one-quarter inch to three-quarter inch particles were used to make the RCA graded material. Natural blue rock and limestone aggregates were pre-blended prior to arrival in the laboratory. Figure 3-2 shows the Gilson sieve machine.

Figure 3-2: Gilson Sieve Machine

The material was organized from specifications given in ASTM C 33.[36] ASTM C 33 defines the requirements for grading and quality of fine and coarse aggregate for use in concrete. The natural blue rock aggregate was a pre-blended number 67 grading obtained from the originating aggregate quarry in Westbrook, Maine.[37] Recycled aggregate was also blended to comply with the number 67 grading requirement. As many factors between the natural blue rock and RCA were kept consistent for comparative purposes.

Specimen Mixing and Curing

All mixing and curing procedures were followed using the ASTM C 305 specification for mortar-bar and prism sized specimens.[38] ASTM C 305 discusses proper methods for mixing hydraulic cement pastes and mortars of plastic consistency with a mechanical mixer. This specification was used for all paste, mortar and concrete mixing throughout this project. Mortar-bar samples were made using a Hobart processing mixer and prism beam, cube, and cylindrical sized specimens were made using a Lancaster Counter Current Batch Mixer. Figures 3-3 and 3-4 show the two mixers.

Figure 3-3: Hobart Processing Mixer

Figure 3-4: Lancaster Counter Current Batch Mixer

Concrete specimen construction was done according to ASTM C 192, which outlines making prism beam specimens.[39] ASTM C 192 discusses standard requirements for the preparation of materials in a concrete mixture, mixing concrete specimens, placing plastic concrete and the curing of concrete specimens in a laboratory setting. Steel molds were made for standard prism beam construction for ASTM C 1293 as seen in Figure 3-5.[19]

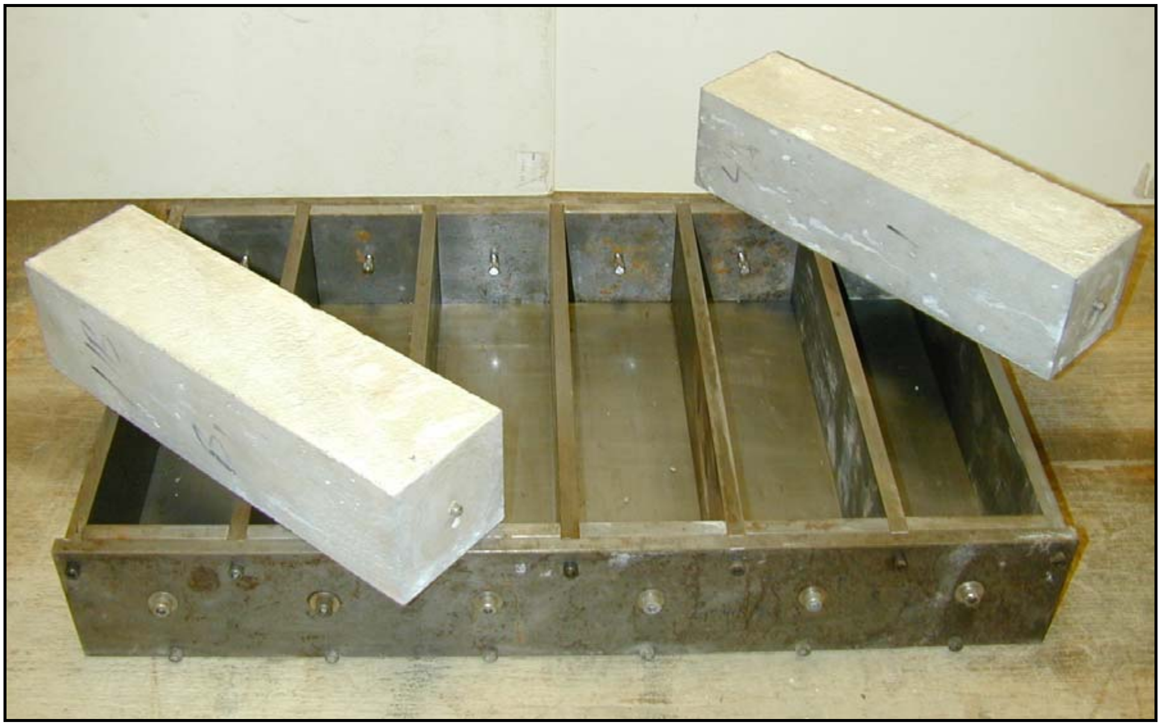


Figure 3-5: Prism Beam Mold

Mortar-bar molds were used, as samples must be made to a precise size, for ASTM C 1260 as seen in Figure 3-6.[18]

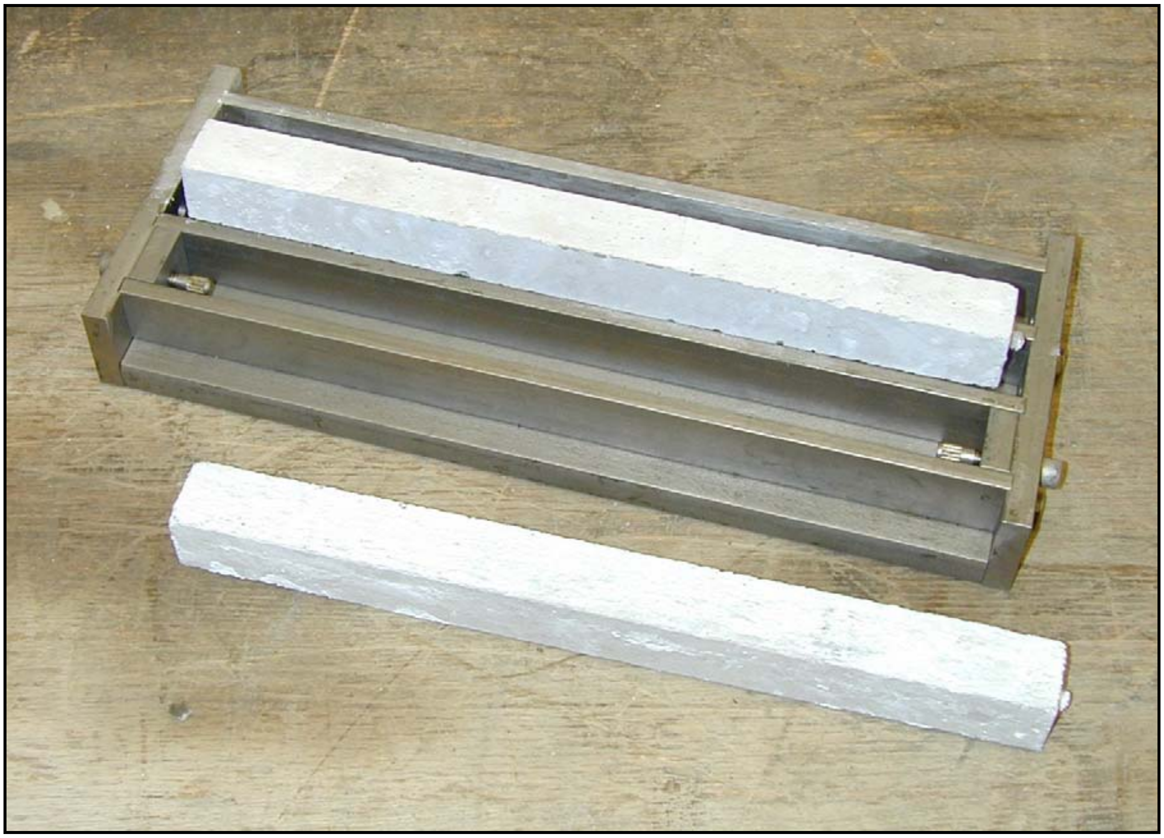


Figure 3-6: Mortar-Bar Mold

All samples were cured in a 100% relative humidity fog room, specially designed for the materials laboratory at the University of New Hampshire. This ensured proper early-age hydration of all paste, mortar and concrete specimens made for this research study.

Specimen Testing

ASTM C 1260 and ASTM C 1293 specifications were used to test concrete samples for this research. The tests were followed in standard form and modifications were made to accommodate for sample size, testing environment and testing duration changes.

The ASTM C 1260 accelerated mortar bar test method allows the detection within sixteen days for potential ASR distress of aggregate. The accelerated test time is due to the testing environment and preparation procedures. The aggregate must be crushed, increasing surface area and fineness of the material, and the concrete mortar bars are submerged in one normal NaOH solution at 80^{o} C. The natural blue rock aggregate and all mitigation strategies were investigated using this test. RCA cannot be used in the mortar bar test due to pulverizing the aggregates matrix. RCA consists as a composite of aggregate in a matrix of paste. The pulverizing process would break the RCA into two particles; paste and aggregate, not testing the material as it appears when applied to full-scale concrete mixes. The blue rock aggregate, recovered from the recycled aggregate particles by an accelerated aging extraction procedure, was tested with ASTM C 1260.[24] This was done to show that the natural aggregate fraction of the recycled aggregate still showed reactive characteristics that would promote ASR distress. Figure 3-7 shows ASTM C 1260 mortar-bar samples in polyethylene containers surrounded by 1N NaOH solution.

Figure 3-7: ASTM C 1260 Mortar-Bar Samples

The ASTM C 1293 test method evaluates a full-scale concrete sample for potential ASR distress in a one-year period. This test uses prism beams, not mortar-bars where aggregate pulverizing is needed, so standard size aggregate particles can be incorporated in the concrete test mixes. This made it possible to make PCC samples with RCA blue rock and natural blue rock aggregate without pulverizing techniques. ASTM C 1293 is the most accepted ASR detection method for full-scale concrete test samples.[20]

The drawback to this procedure is a one-year test duration for samples made with straight cement and a two-year test duration with cement substitution concrete mixtures, when fly ash, GGBFS and silica fume are incoprporated. Figure 3-8 shows the ASTM C 1293 prism beam sitting on a spacer and the container.

Figure 3-8: ASTM C 1293 Prism Beam and Storage Container

ASTM C 1260 mortar-bar test method was used as an initial screening process to show the effects of the mitigation strategies on the natural blue rock aggregate. This test was also done on recycled blue rock that was stripped away from the paste fraction of the recycled material.[24] This information was used to apply the mitigation strategies with ASTM C 1293 and compare concrete samples made with natural blue rock and blue rock RCA. It is recommended that ASTM C 1260 and ASTM C 1293 testing procedures be used together for proper aggregate and concrete ASR potential classification.[20]

Modifications were made to both of the previously mentioned tests that will be explained in further detail later in this chapter.

All ASTM C 1293 testing samples were placed in a controlled oven to keep temperatures at the required testing limit. The oven was accurate to 0.2 degrees Celsius. Figure 3-9 shows the testing oven used for ASTM C 1293 standard prism beam and vacuum-sealed cube samples.

Figure 3-9: ASTM C 1293 Testing Oven

ASTM C 227 is not a recommended test and was not used in this study. This test incorporates a six-month testing duration and it would not be applicable with RCA concretes as the aggregate cannot be crushed and then realistically evaluated.

Modified Testing Procedures

Preliminary testing was conducted to investigate new testing procedures modifying current ASTM tests. Results from this testing and literature reviews led to two modified procedures for both the ASTM C 1260 and ASTM C 1293 tests.[25] The objective of modifying standard testing procedures was to obtain ASR expansion data in a shorter duration to predict material properties when subjected to conditions where ASR distress may occur.

ASTM C 1260 Prism Beam

The ASTM C 1260 mortar bar test was modified so that RCA samples could be evaluated in the accelerated test procedure. The modified ASTM C 1260 procedure was adopted from work done by Benoit Fournier at the International Centre for Sustainable Development of Cement and Concrete.[40] The prism beams from the ASTM C 1293 standard prism beam test are used allowing full-scale concrete samples to be evaluated. The test duration is 28-days in a 1N NaOH environment, doubling the ASTM C 1260 mortar-bar test, with a failure expansion criteria of 0.04% from 0.10%. Benoit Fournier developed this expansion criteria based on correlations from field data and past ASTM C 1293 standard prism beam test results. This allows for much faster test results than the one-year duration period for the ASTM C 1293 test. This modified testing procedure provides a rapid test environment for RCA concrete.

ASTM C 1260 Cube

Along with prism beams, ASTM C 1260 was further modified to include 76.2-millimeter square cubes with four 6.35-millimeter diameter holes cast into them. The cube shape has increased surface area to volume ratio. The cast holes in the cube sample allowed for the one normal NaOH solution to penetrate the sample faster and increase the reaction rate for potential ASR distress. Promising results have been published with the cube samples showing accelerated expansions in the ASTM C 1260 test environment.[41] Figures 3.10 and 3.11 shows a plan and section view of a ASTM C 1260 cube sample and

Figure 3-12 shows an example of the modified ASTM C 1260 prism beam and modified ASTM C 1260 cube test specimens.

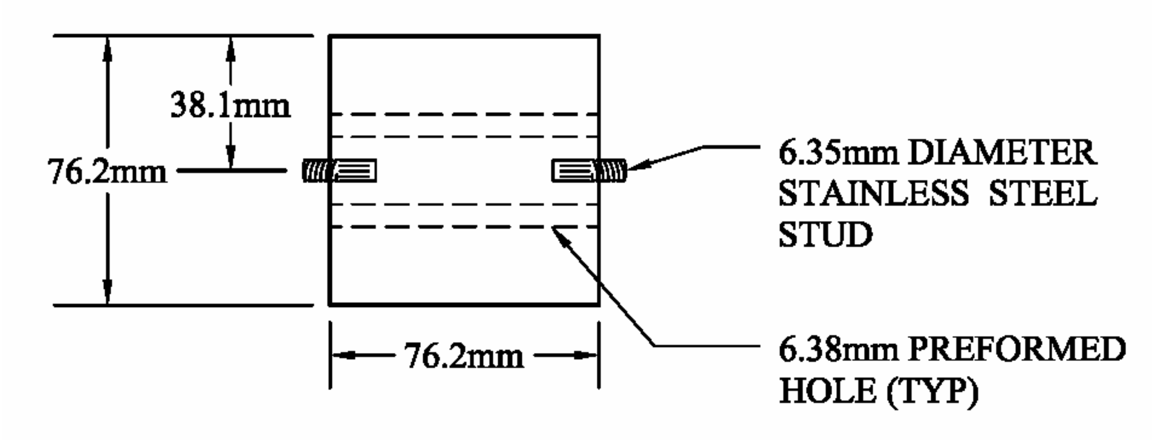


Figure 3-10: ASTM C 1260 Cube Plan View

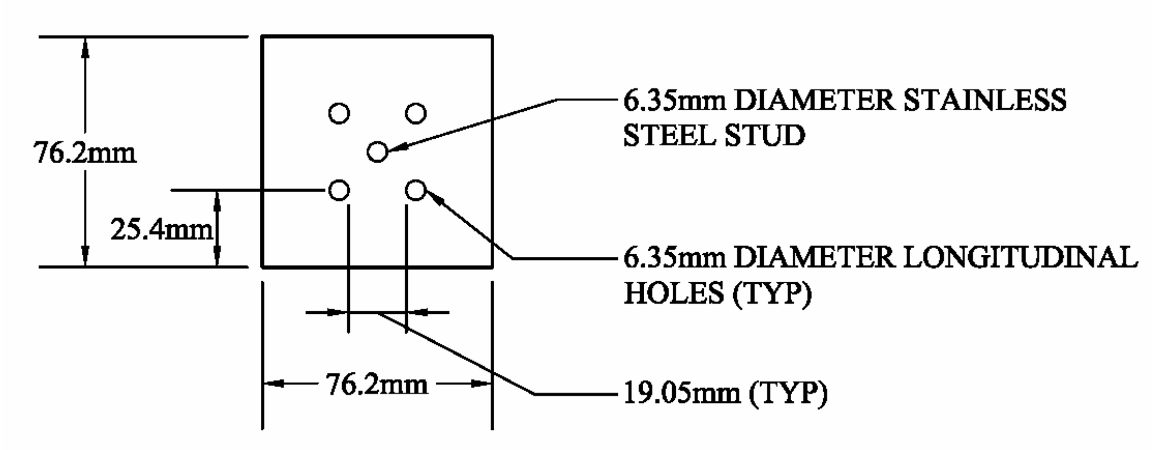


Figure 3-11: ASTM C 1260 Cube Section View

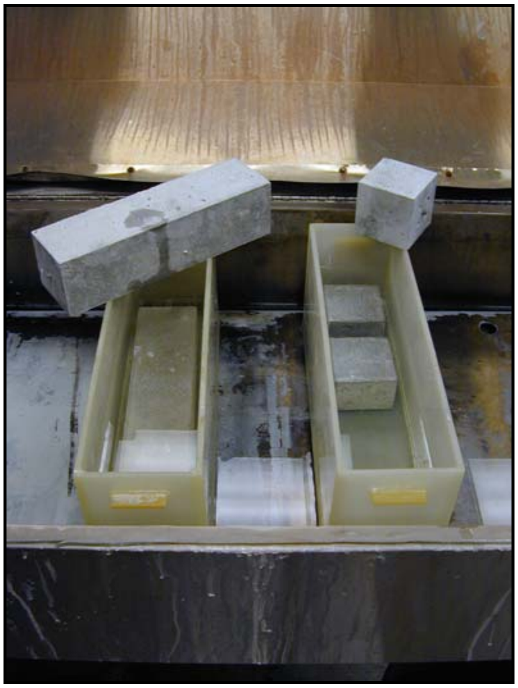


Figure 3-12: ASTM C 1260 Prism Beam and Cube Test Specimens

These two procedures are not approved in ASTM testing procedures, however it has been shown that these accelerated tests correlate well with the highly accepted ASTM C 1293 standard prism beam test.[41,42]

ASTM C 1293 Cube

One modified ASTM C 1293 test incorporated the use of 76.2-millimeter square cubes with four 6.35-millimeter diameter holes cast into them, vacuum-sealed with enough water to blanket the surface area of the cubes. The samples are sealed so as to make a more uniform moisture state than achieved by the standard ASTM C 1293 test. The testing temperature is the same as for the ASTM C 1293 standard prism beam test, only the sample size and moisture state differs. The increased surface area ratio is incorporated to speed the reaction and gain results that show sample reactivity in a shorter testing duration than one-year. Promising results have been published with the cube samples showing greatly accelerated expansions in the ASTM C 1293 test environment.[41] Referenced test results showed the one-year testing time, for ASTM C 1293 standard prism beam testing, can be decreased to fifty days with cube samples.[25] Figures 3-13 and 3-14 show cube samples in mold and testing environments.

Figure 3-13: Modified ASTM C 1293 Cube Sample

Figure 3-14: Modified ASTM C 1293 Vacuum-Sealed Cube Sample

ASTM C 1293 Electrical Cylinder

Another modification to the ASTM C 1293 testing procedure was the introduction of electrical current to the concrete sample. Cathodic protection has been used to protect steel in reinforced concrete structures, but can also promote ASR. The application of electrochemical systems to retard the corrosion of the reinforcement in concrete structures increases the hydroxyl ion concentration within the concrete and may increase the risk of alkali-silica reaction.[43] Reinforcing steel corrosion in concrete occurs as a flow of electrical current is connected between the anodic and cathodic surfaces of the steel in question, but this may be eliminated by controlling the magnitude and direction of the current flow. Cathodic protection in steel reinforced concrete structures works by reversing the current back to the original anodic steel surface, thus making the steel cathodic so it does not corrode.[44] The cathodic reaction produces hydroxyl ions and alkali ions present in the concrete that are attracted to the negatively charged steel due to potential gradients. This causes an increase in the alkalinity of the concrete that can cause attack on ASR reactive aggregates. This cathodic protection, although protecting reinforcing steel may induce ASR in the concrete structure that may not have been triggered without the increased formation of hydroxyl ions.[43] Numerous research projects and studies have been aimed at the cause of ASR from cathodic protection mechanisms.[45,46,47]

These samples were cast in four inch by eight-inch cylinder molds, thus changing the test sample size from a standard prism beam. Both ends of the cylinders were coated with conductive carbon paint for uniform electrical current flow. This gave each sample a cathode and anode the same size as the area of the end of the cylinder. The hypothesis was that electrical current applied across the ends of the concrete cylinders would initiate ASR and induce distress faster than in the ASTM C1293 prism beam test. The driving force to accelerate ASR in these concrete samples is ion migration of hydroxyl ions by an electrical gradient. The hydroxyl ions moving within the concrete have a greater chance to pass reactive aggregate with the added energy from the electrical source. Figure 3-15 shows an electrical cylinder.

Figure 3-15: Modified ASTM C 1293 Electrical Cylinder

These two procedures are not approved in ASTM testing manuals, but published articles show evidence that results can be achieved much faster than with the accepted

ASTM C 1293 standard prism beam testing procedure with good correlation to accepted ASR ASTM testing.[41,45,46,47]

Specimen Measuring

ASTM C 490 was used to determine specimen length change and expansion behavior.[48] This specification was followed for measuring all concrete specimens. Figure 3-16 shows a cube and prism beam in the measurement devices. The prism beam measuring device was accurate to four decimal places, while the cube measuring device was accurate to five decimal places.

Figure 3-16: Cube and Prism Beam Measuring Devices

Material Property Testing

Aggregate properties and characteristics were gathered through various ASTM testing procedures.

The specific gravity and absorption characteristics of the fine aggregate used in this study, Ossipee glacial sand, was determined according to ASTM C 128.[49]

The specific gravity and absorption characteristics of the course aggregates used in this study; natural blue rock quartzite, recycled blue rock quartzite and limestone, were determined with ASTM C 127.[50]

The dry-rodded unit weight and percent voids of the course aggregates was determined using ASTM C 29/29M.[51] It was observed that the natural blue rock aggregate has a larger dry-rodded unit weight value than the recycled aggregate and fewer voids.

All cements used in this study; high alkali cement, low alkali cement and silica fume blended cement met the specifications for ASTM C 150 and ASTM C 1157.[52,53]

The class F fly ash met the specification for ASTM C 618.[54] The mill analysis is included in appendix A.

The ground granulated blast furnace slag met the specification for ASTM C 441.[55]

The silica fume met the specification for ASTM C 1240.[56]

A test procedure was used to investigate water-soluble alkali content of the concrete mix materials.[57] The major source of alkali contribution in concrete is cement, but it was important to know if other materials, RCA or other coarse and fine aggregates, supplied quantities of alkali to the concrete. Natural blue rock aggregate and blue rock RCA were subjected to this testing procedure.

A test procedure was used to investigate total alkali contents for aggregate materials used in this study.[58] The aggregates were tested to obtain data that was used with the lithium nitrate mitigation procedure, which was added to a concrete mixture based on the total alkali of the PCC mixture in question.

TESTING DEVELOPMENT

ASTM C 1260 (mortar-bar method), ASTM C 1293 standard prism beam and the modified version of ASTM C 1260 prism beam were evaluated. Although the modified ASTM C 1260 prism beam test is not a standard ASTM test it has shown comparable results to ASTM C1293 standard prism beam results with this research and past research performed by Benoit Fournier.[40]

PRELIMINARY TESTING

The electrical cylinder molds were standard four by eight inch cylinders. End plugs were cast into the cylinders and removed after a 24-hour curing period so that stainless steel or copper measuring studs could be grouted into the samples. Figure 3-17 shows the calibration jig used to grout measuring studs into the electrical cylinders and Figure 3-18 shows the calibration jig and a cylindrical sample with studs grouted.

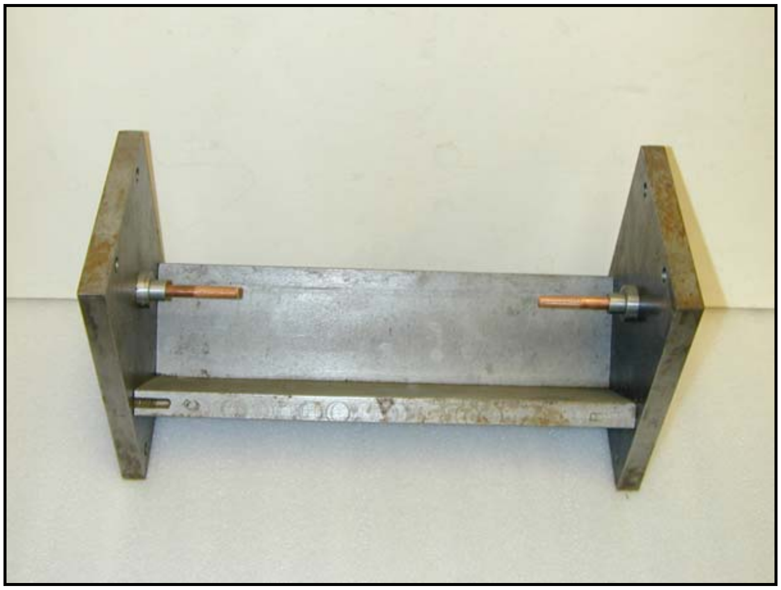


Figure 3-17: Cylinder and Core Calibration Jig

Figure 3-18: Cylinder Calibration Jig with Finished Sample

This allowed the electrical cylinders to have the same overall length as the standard prism beams so the same measuring instruments could be used with both concrete samples and direct comparisons could be made between data.

The testing environment for the electrical cylinders was the same as for the ASTM C 1293 standard prism beam test, with electrical source wires inserted through holes in the side of the testing cylinder to run electrical current to the samples measuring studs (see Figure 3-15).

Alligator clips, connected to the electric current supply wires, attach to the measuring studs to carry the current into the sample. The electrical wires were plugged into a power source that emitted one milliamp of constant dc current into the concrete samples. Figure 3-19 shows the electrical power source, which supplied a one-milliAmp current to each sample, with a current density of 112.0 mA/m^2. Past research showed current densities over 50 mA/m^2 may have a positive effect and cause expansions to increase in concrete samples.[47] This current density was used as it showed the highest expansion characteristics with preliminary research done on electrical cylinders prior to this research beginning. Figure 3-20 shows the testing oven for the electrical cylinder samples.

Figure 3-19: Modified ASTM C 1293 Electrical Cylinder with Power Source

Figure 3-20: Electrical Cylinder Testing Oven

MIX DESIGNS

Mix design criteria were developed from the ASTM C 1293 standard prism beam test specification. The mix design was based on the absolute volume method, which is outlined in the Portland Cement Association: Design and Control of Concrete Mixtures engineering bulletin.[59] All concrete mixtures shared a common water-cement ratio, cement content, air entrainment content and coarse aggregate ratio. Total alkali content was different for mixtures depending on cement and/or mitigation strategies incorporated into concretes. Fine aggregate contents varied between the RCA and natural aggregate concretes so the yield could be controlled. Limestone aggregate was used with the control cement and low alkali cement to show if any ingredients in the concrete mixtures, other than reactive coarse aggregate, would promote ASR expansion. No mitigation strategies were incorporated into Limestone coarse aggregate mixtures, as the aggregate was innocuous. The following overview outlines all concrete mixtures investigated in this study.

Material Overview:

Aggregates (Coarse):

A – South Wallingford Limestone
B – Westbrook Blue Rock
C – RCA Westbrook Blue Rock

Mitigation Strategies:

E – Low Alkali Cement
F – Silica Fume Blended Cement
G – Class F Fly Ash
H – GGBFS
I – Lithium Nitrate ($LiNO_3$)

Cement:

D – High Alkali Dragon Cement

Admixture:

J – Air Entrainment (Darex II)

Aggregate (Fine):

K – Ossipee Glacial Sand

(Note: a - represents low mitigation & b - represents high mitigations for G & H)

Low alkali and silica fume blended cement were substituted in full for the high alkali cement. The class F fly ash was substituted with the high alkali cement at 15% and 25% percent based on total weight of the cement. The GGBFS was substituted in the same way as for the class F fly ash, but at 25% and 50% of the total weight of the cement. Lithium nitrate required no cement substitution and was added to a concrete mixture based on the total alkali content. Table 3-1 presents the mix design for all mixes for this research.

Table 3-1: Concrete Mix Design Specifications

Mix Component	**Design Property**
Water-Cement Ratio (W/C)	0.45
Cement Content	708 lb/yd^3
Maximum Aggregate Size	0.75 inches
Air Entrainment Content	6%
Volume of Coarse Aggregate Per Unit of Volume of Concrete	0.63

Mixture Overview

Initial testing was done on eighteen concrete mixtures. Table 3-2 shows the mixture outlines with individual ingredients represented with letters corresponding to the above material overview sub-section.

Table 3-2: Mix Designs and Testing Properties

Concrete Mixture	**Mixture Components**	**Testing Conditions** (a)
1	A, D, J & K	1, 2, 3, 4, 5 & 6
2	A, E, J & K	1, 2, 3, 4, 5 & 6
3	B, D, J & K	1, 2, 3, 4, 5 & 6
4	B, E, J & K	1, 2, 3, 4, 5 & 6
5	B, D, G_a, J & K	1, 2, 3, 4, 5 & 6
6	B, D, G_b, J & K	1, 2, 3, 4, 5 & 6
7	B, D, H_a, J & K	1, 2, 3, 4, 5 & 6
8	B, D, H_b, J & K	1, 2, 3, 4, 5 & 6
9	B, F, J & K	1, 2, 3, 4, 5 & 6
10	B, D, I, J & K	1, 2, 3, 4, 5 & 6
11	C, D, J & K	1, 2, 3, 4, 5 & 6
12	C, E, J & K	2, 3, 4, 5 & 6
13	C, D, G_a, J & K	2, 3, 4, 5 & 6
14	C, D, G_b, J & K	2, 3, 4, 5 & 6
15	C, D, H_a, J & K	2, 3, 4, 5 & 6
16	C, D, H_b, J & K	2, 3, 4, 5 & 6
17	C, F, J & K	2, 3, 4, 5 & 6
18	C, D, I, J & K	2, 3, 4, 5 & 6

Note (a):

ASTM C 1260 Testing:	ASTM C 1293 Testing:
1 – Mortar-Bar Method	4 – Standard Prism Beam
2 – Modified Prism Beam	5 – Modified Cube (Vacuum Sealed)
3 – Modified Cube	6 – Modified Electrical Cylinders

CHAPTER 4

RESULTS

INTRODUCTION

All data obtained from this study are a direct result of testing concrete samples for potential deleterious ASR expansions as per ASTM testing specifications and modifications to these tests.

PRELIMINARY TEST DEVELOPEMENT

ASTM C 1260 and 1293 tests, including modified testing, had been performed and further developed at the University of New Hampshire before this research began.[25,41] No preliminary testing was needed to change the tests or alter them in any way other than the electrical testing, which was altered for the use of four inch diameter by eight inch long cylinders.

Modifications to established ASR testing was done to decrease the testing duration needed to gain results for ASR potential of a PCC mixture. Past results had shown cube samples to increase expansion rates compared to prism beam samples. Along with high early expansions, there was high variation with cube results. This could be overcome with stringent measuring techniques and a sound measuring schedule.[25] Cube samples were used, as testing times could potentially be reduced by a factor of six. Electrical testing was adopted with positive preliminary results. Expansions could be accelerated with an increased electrical current density applied to the samples. These modified results were compared to results from accepted ASTM tests so that failure limits could be established.

TESTING RESULTS

All mitigation strategies used in this testing are established and have shown favorable results in controlling ASR potential with natural aggregate PCC.[3]

Rapid Testing Procedures

ASTM C 1260 (Mortar-Bar Testing)

Studies initiated with ASTM C 1260 mortar-bar testing to screen the aggregates being used in this study for characterization as ASR reactive, potentially reactive, or non-reactive. Natural blue rock and limestone aggregates were tested to determine if mitigation strategies were needed to control deleterious ASR expansion and that the ingredients in the mixtures, besides reactive aggregate, would not promote ASR distress on their own. Recycled aggregate blue rock was reclaimed from its RCA and tested within a ASTM C 1260 mortar-bar environment. This gave evidence that aggregate within the RCA still contained potential for ASR distress.

Results from ASTM C 1260 mortar-bar testing show a non-reactive aggregate with expansion below 0.10% after fourteen days, a potentially reactive aggregate with expansion between 0.10% and 0.20% after fourteen days, and a reactive aggregate with expansion above 0.20% after fourteen days. Testing durations were doubled when cement substitution mitigations was used; class F fly ash, GGBFS, and silica fume. This holds true for all the tests performed in this research.

Figure 4-1 shows expansion results for limestone aggregate with high and low alkali cement. Two mortar-bar tests were run using the high alkali and low alkali cements with the aggregate. The aggregate showed non-reactive results with both cements as expansion levels were below 0.10% at fourteen days. This showed that all other substances, other than the coarse aggregate, did not initiate ASR expansions as per the 0.10% limit.

Mortar-Bar testing was performed on natural blue rock aggregate that included all mixtures outlined from the previous section as presented in Figures 4-2 through 4-6.

Figure 4-2 shows expansion results for natural blue rock aggregate with high and low alkali cement and recycled blue rock aggregate with high alkali cement. It was observed that both aggregate sources, natural and recycled, showed potentially reactive ASR expansion with high alkali cement with expansion levels between 0.10% and 0.20%. Natural blue rock aggregate showed potential ASR distress with low alkali cement, as was expected, with expansion levels between 0.10% to 0.20%. These results initially show that the aggregate sources in question are susceptible to ASR distress if proper mitigation strategies are not incorporated.

The low alkali cement is not an acceptable mitigation material with the ASTM C 1260 mortar-bar test. This was due to the testing environment where alkali sources are plentiful from the surrounding one-normal NaOH solution that the concrete samples are submerged within. The low alkali cement is an effective mitigation strategy as it keeps alkali concentrations low within a concrete mixture. Concrete pore solution is not able to break down ASR reactive aggregates, if the hydroxyl ion concentration of the solution is kept below a threshold level. ASTM C 1260 testing environment is not an effective way to investigate the ability of low alkali cement to mitigate ASR. Low alkali cement was not used in further testing where samples were submerged in one-normal NaOH solution.

Testing the aggregates without mitigation strategies showed that high alkali cement alone could not eliminate the potential of ASR distress. It was necessary to incorporate the mitigation strategies to the mortar-bar samples in order to try to decrease expansion levels below 0.10%. The remaining testing was done with natural blue rock aggregate only, as the recycled blue rock extraction process from the recycled blue rock aggregate was extremely time consuming and conservation of the material for other testing was necessary with a limited supply of material available.

All remaining graphs include the natural blue rock with high alkali cement control data as a reference to show if mitigation strategies are more effective in mitigating ASR distress.

Figure 4-3 shows expansion results for natural blue rock aggregate with low and high class F fly ash mitigations. Class F fly ash was substituted for high alkali cement at 15% and 25% by weight of original cement. Class F fly ash mitigation controlled ASR expansion below non-reactive limits for the 25% mitigation. The 15% mitigation level allowed expansion levels to exceed 0.01%, showing potentially reactive behavior.

Figure 4-4 shows expansion results for natural blue rock aggregate with low and high GGBFS mitigations. GGBFS was substituted for high alkali cement at 25% and 55% by weight of original cement content. The 25% mitigation allowed expansion levels to exceed 0.10%. The 55% mitigation controlled expansion levels below non-reactive limits.

Figure 4-5 shows expansion results for natural blue rock aggregate with 100% lithium nitrate mitigation. Lithium nitrate mitigation controlled expansion levels below non-reactive limits.

Figure 4-6 shows expansion results for natural blue rock aggregate with 8% silica fume mitigation. The expansion was between 0.01% and 0.20%, showing potentially reactive characteristics.

Expansion levels exceeded non-reactive criteria of 0.10% for low mitigation strategies of class F fly ash, GGBFS, and silica fume blended cement. The potentially expansive category results need to be further explored with continued testing to get a more accurate representation of the mixture characteristics. These results were verified with ASTM C 1293 standard prism beam testing (the other ASTM testing procedure presently recognized as an accepted ASR potential test method).

The addition of mitigation materials showed positive results, as all expansions were smaller than natural blue rock aggregate and high alkali cement used alone. From ASTM C 1260 mortar-bar results, it was observed that 25% class F fly ash mitigation, 55% GGBFS mitigation, and one-hundred percent lithium nitrate mitigation controlled ASR expansion below non-reactive limits, with a potentially reactive aggregate used with high alkali cement. Silica fume blended cement, containing 8% silica fume, showed potential for controlling expansion.

ASTM C 1293 standard prism beam testing and other modified ASTM tests were performed to further evaluate ASTM C 1260 mortar-bar results for validity.

Figure 4-1: Expansion versus time for ASTM C 1260 (limestone)

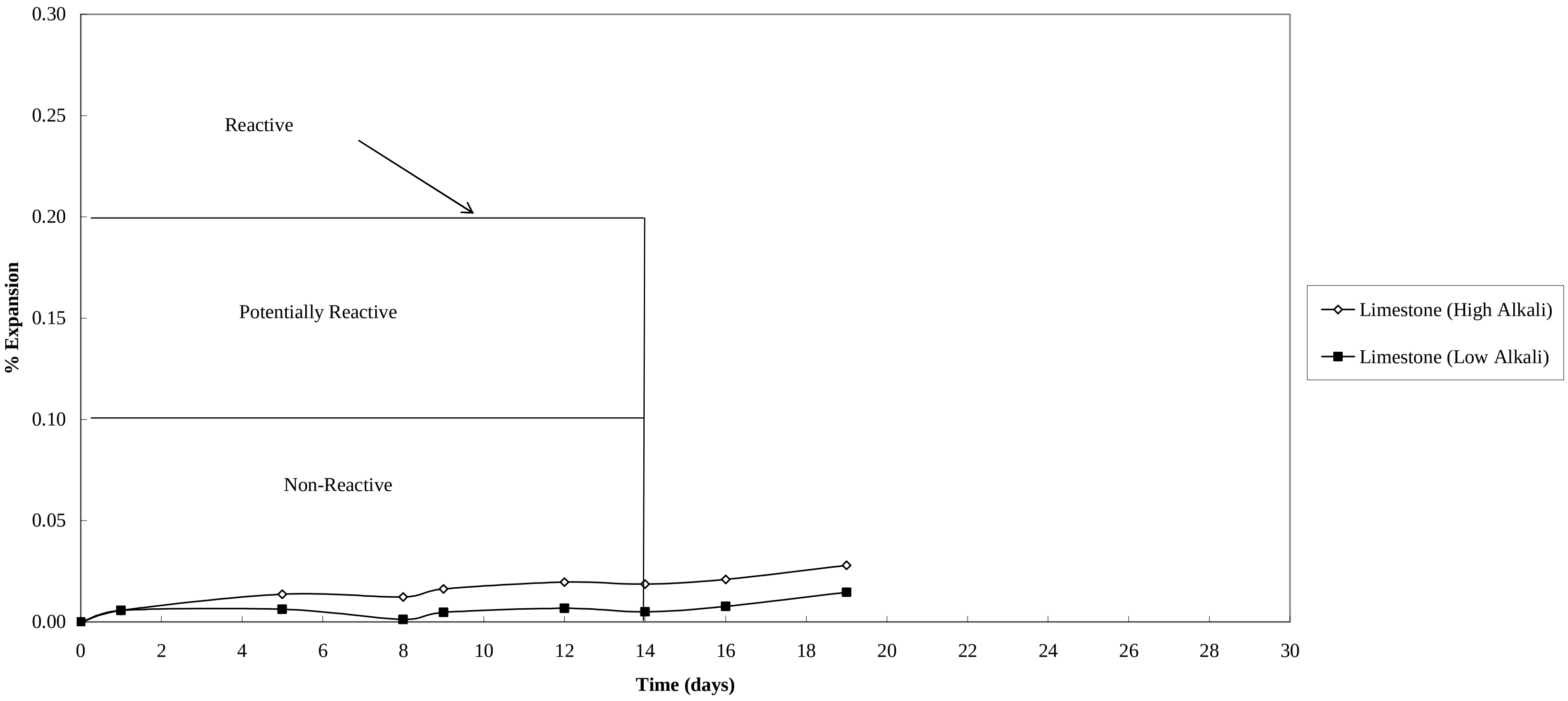


Figure 4-2: Expansion versus time for ASTM C 1260 (natural blue rock and RCA)

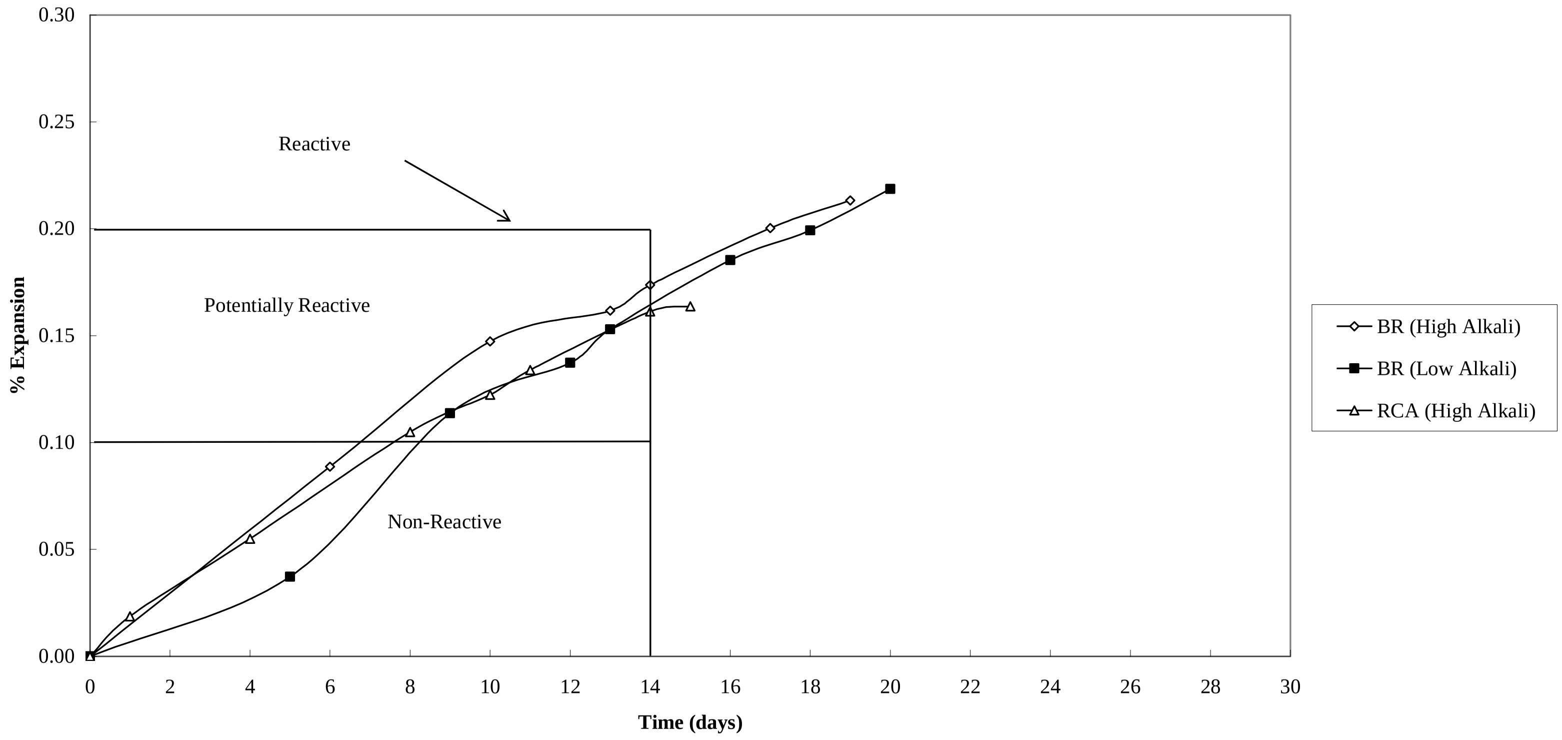


Figure 4-3: Expansion versus time for ASTM C 1260 (natural blue rock and class F fly ash)

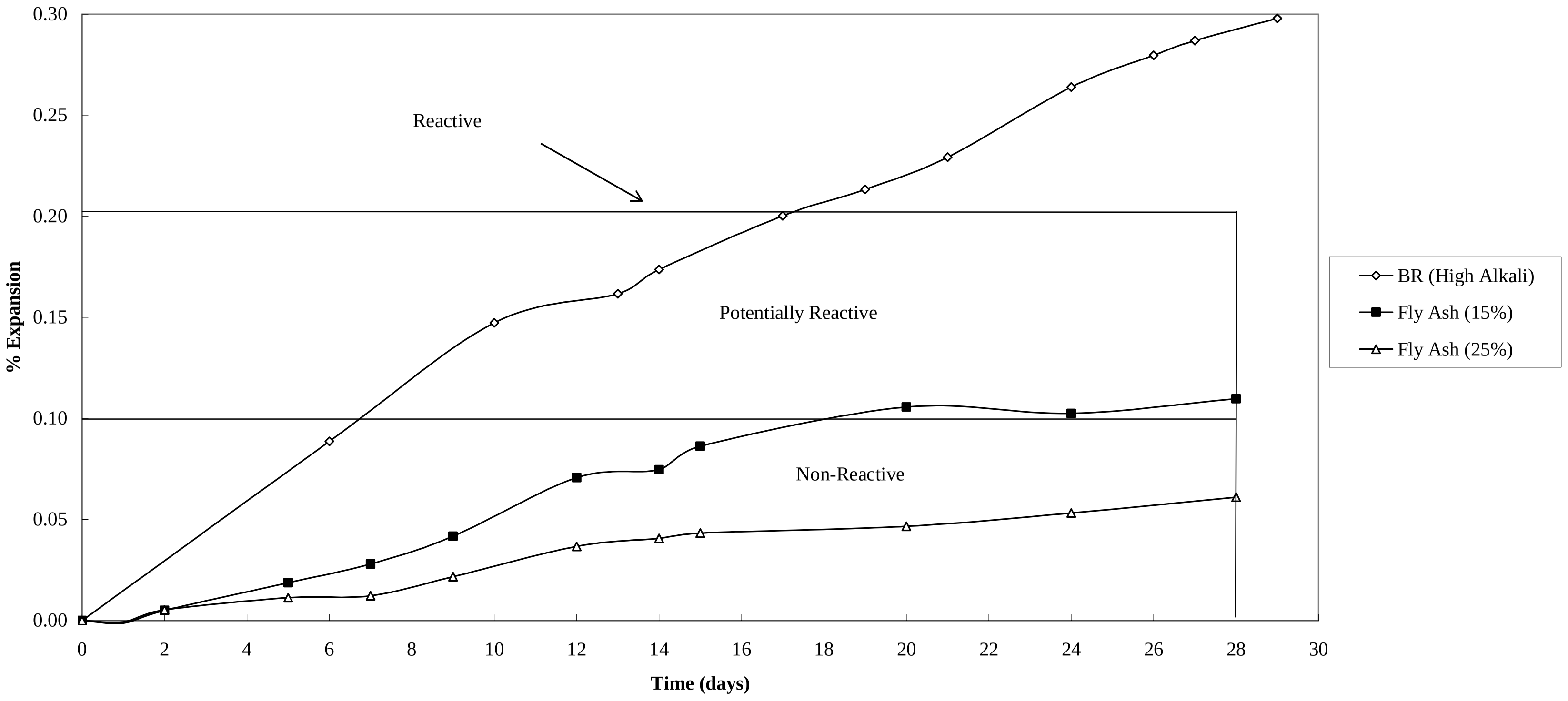


Figure 4-4: Expansion versus time for ASTM C 1260 (natural blue rock and GGBFS)

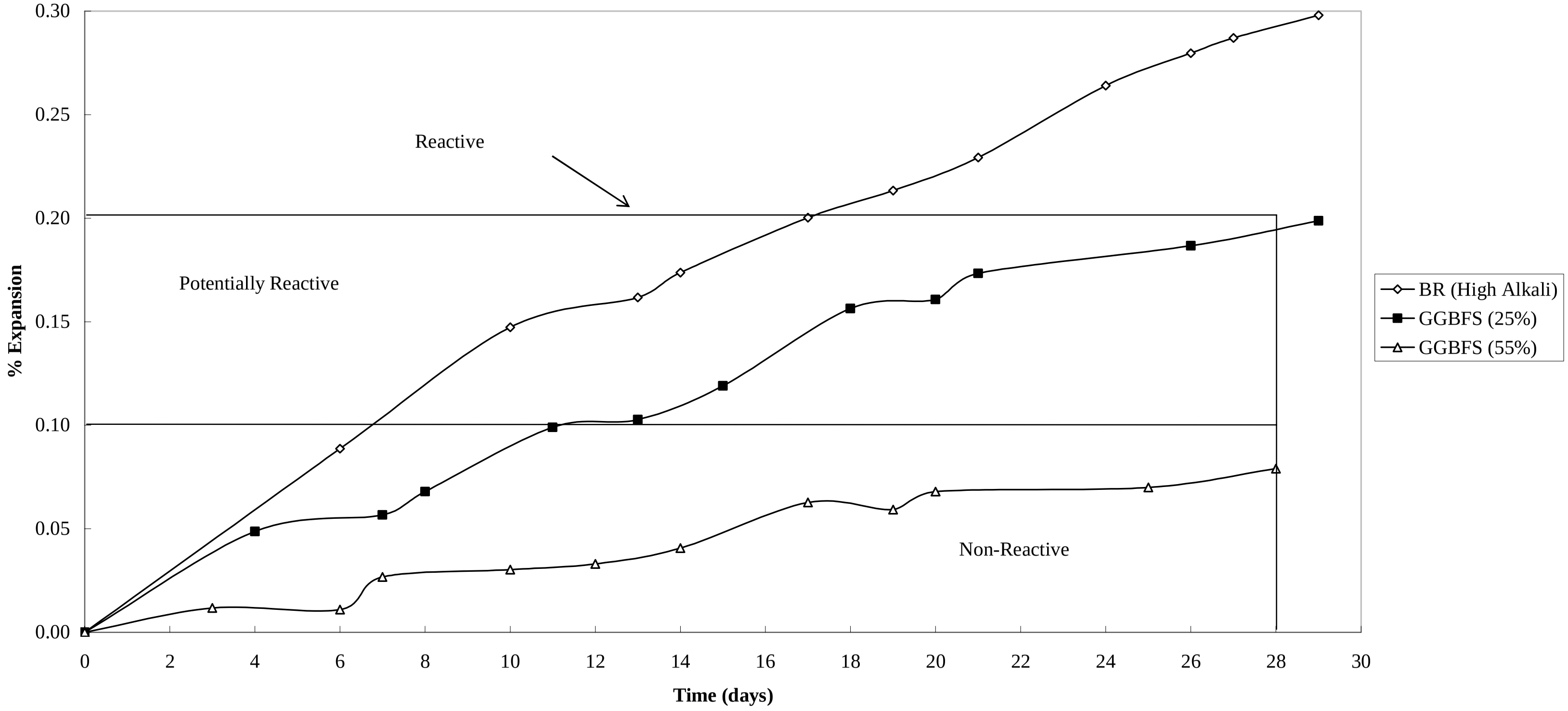


Figure 4-5: Expansion versus time for ASTM C 1260 (natural blue rock and lithium nitrate)

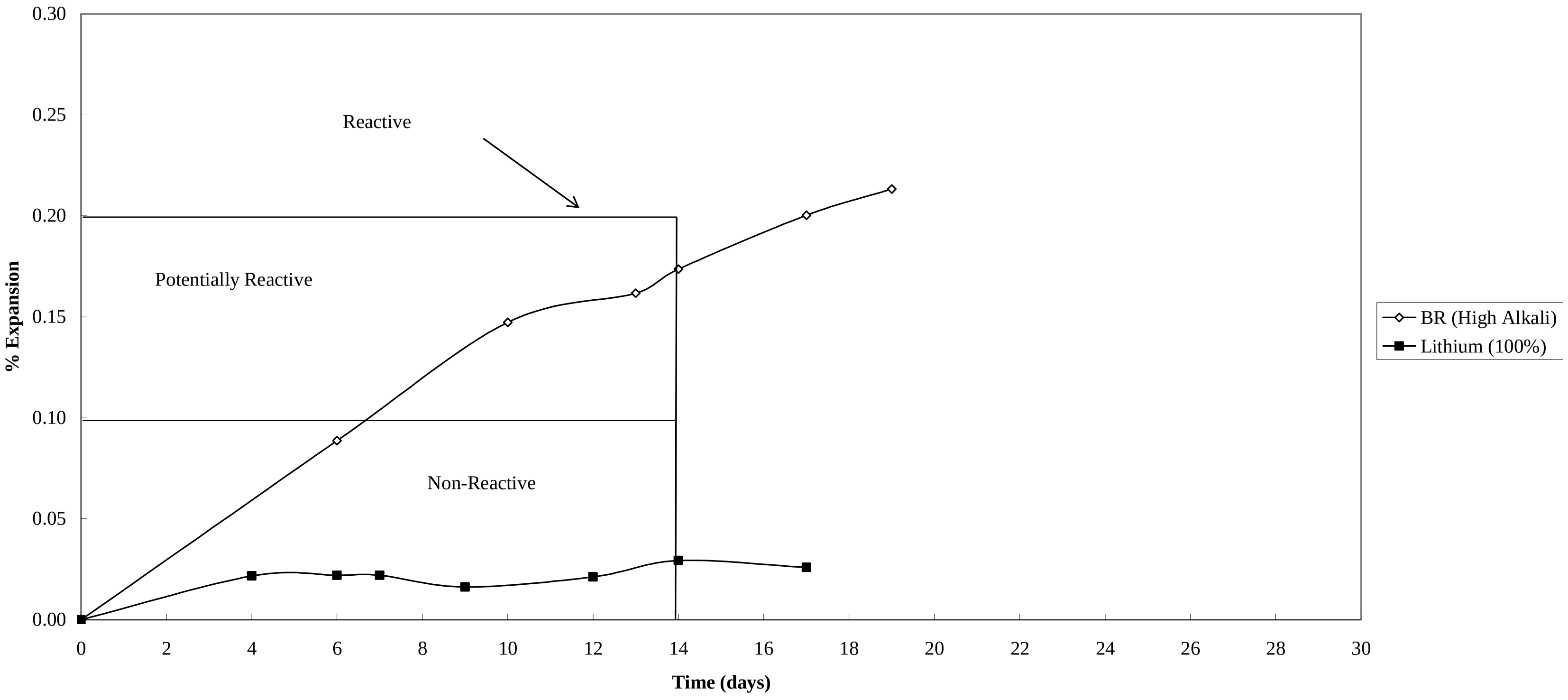
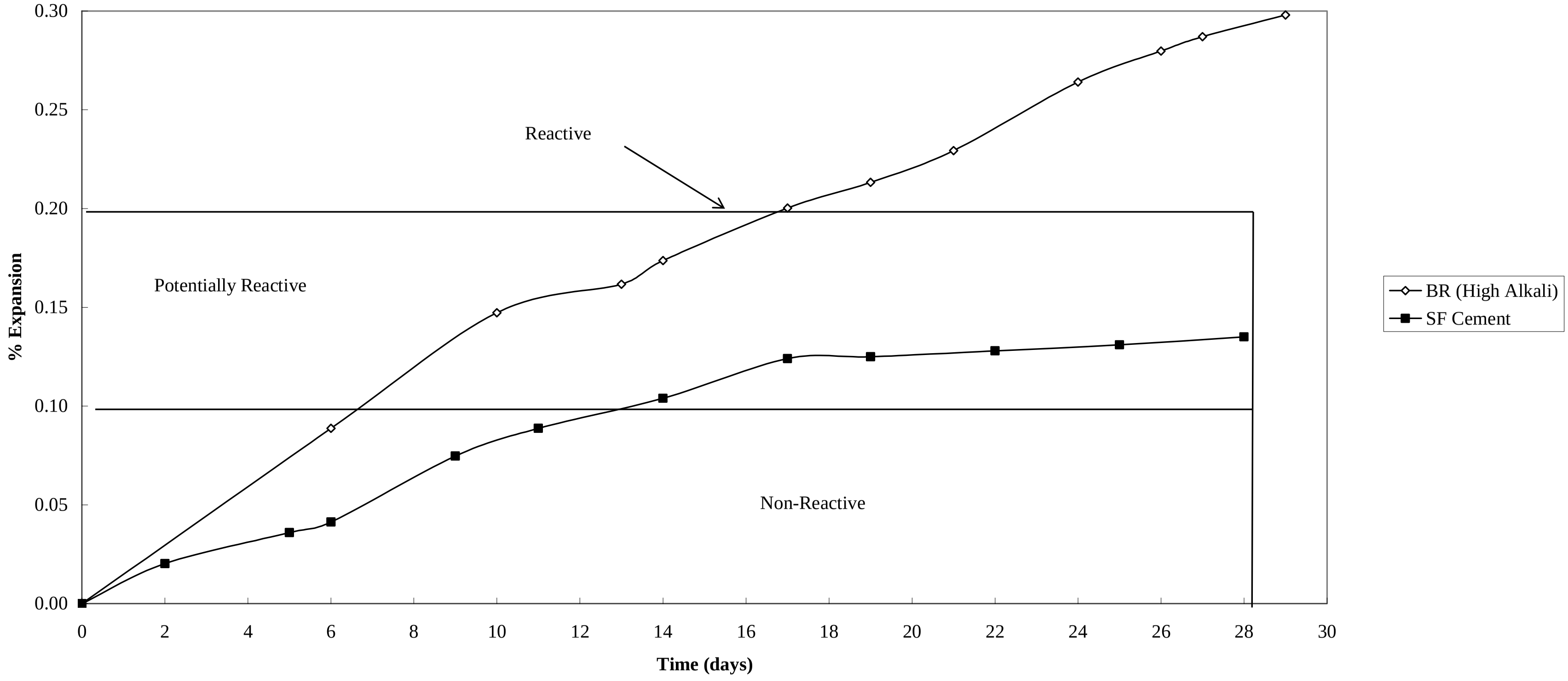


Figure 4-6: Expansion versus time for ASTM C 1260 (natural blue rock and silica fume)



ASTM C 1260 (Modified Prism Beam Test)

ASTM C 1260 modified prism beam testing was performed to further evaluate ASTM C 1260 mortar-bar results for similar conclusions and validity among data.

Results from ASTM C 1260 modified prism beam testing show a non-reactive aggregate with expansion below 0.04% after twenty-eight days and a reactive aggregate with expansion above 0.04% after twenty-eight days.

Figure 4-7 shows expansion results for limestone aggregate with high and low alkali cement. The aggregate showed non-reactive results with both cements as expansion levels were below 0.04%.

Modified prism beam testing was performed on natural and recycled blue rock aggregate that included all mixtures outlined from the previous section as presented in Figures 4-8 through 4-12. The recycled aggregate was incorporated into all remaining tests as no aggregate pulverizing was necessary.

Figure 4-8 shows expansion results for natural and recycled blue rock aggregate with high alkali cement. It was observed that both aggregate sources, natural and recycled, showed reactive ASR expansion with high alkali cement with expansion levels greater than 0.04% at twenty-eight days. These results initially show that the aggregate sources in question are susceptible to ASR distress if proper mitigation strategies are not incorporated.

These results show that mitigation strategies are necessary to control deleterious ASR expansion. Similar results were observed from ASTM C 1260 mortar-bar testing which showed good correlation between an accepted ASTM and this modified test.

Testing the aggregates without mitigation strategies showed that high alkali cement alone could not eliminate the potential of ASR distress. It was necessary to incorporate the mitigation strategies to the prism beam samples in order to try to decrease expansion levels below 0.04%. The remaining testing was done with natural and recycled blue rock aggregates.

Figure 4-9 shows expansion results for natural and recycled blue rock aggregate with low and high class F fly ash mitigations. Class F fly ash mitigation controlled ASR expansion below reactive limits for natural blue rock with 15% and 25% mitigation. Both mitigation levels allowed expansion levels to exceed 0.04% with the recycled blue rock, showing reactive behavior. These results were similar to ASTM C 1260 mortar-bar testing as high mitigation controlled ASR expansion with blue rock aggregate.

Figure 4-10 shows expansion results for natural and recycled blue rock aggregate with low and high GGBFS mitigations. The low mitigation was not suitable to control expansions below 0.04% for either aggregate. The 55% mitigation controlled expansion levels below 0.04% for both aggregates. These results are consistent with ASTM C 1260 mortar-bar results as high mitigation controlled ASR expansion with blue rock aggretate.

Figure 4-11 shows expansion results for natural and recycled blue rock aggregate with 100% lithium nitrate mitigation. Lithium nitrate mitigation showed control over 0.04% expansion with both aggregates. These results are consistent with ASTM C 1260 mortar-bar results as 100% mitigation controlled expansion with blue rock aggregate.

Figure 4-12 shows expansion results for natural and recycled blue rock aggregate with 8% silica fume mitigation. The expansions were both over 0.04%, which showed the mitigation strategy was not able to control ASR expansion below reactive limits.

These results are consistent with ASTM C 1260 mortar-bar results, as the 8% silica fume mitigation did not control expansion with blue rock aggregate.

ASTM C 1260 modified prism beam testing showed consistent results with ASTM C 1260 mortar-bar testing results. The data suggests that these ASR testing procedures can be used with one another for comparative purposes to evaluate the characteristics of a potential ASR reactive aggregate. Modified prism beam results, correlating well to ASTM C 1260 mortar-bar testing, show it can be used as a rapid test procedure to evaluate full scale concrete samples (thus incorporating the recycled aggregate). This allows RCA concretes to be tested in a rapid test environment.

Twenty-five percent Class F fly ash mitigation, 55% GGBFS substitution, and 100% lithium nitrate dosage controlled ASR expansion for natural and recycled blue rock aggregate with the modified ASTM C 1260 prism beam test. Further ASR testing was necessary to evaluate full-scale concrete samples in a less aggressive environment, relating closer to a "real world" situation that concrete may experience. If both tests show comparative results to characterize ASR then conclusions can be made to the potential for ASR distress for a PCC mixture.

Figure 4-7: Expansion versus time for ASTM C 1260 (modified prism beam test) (limestone)

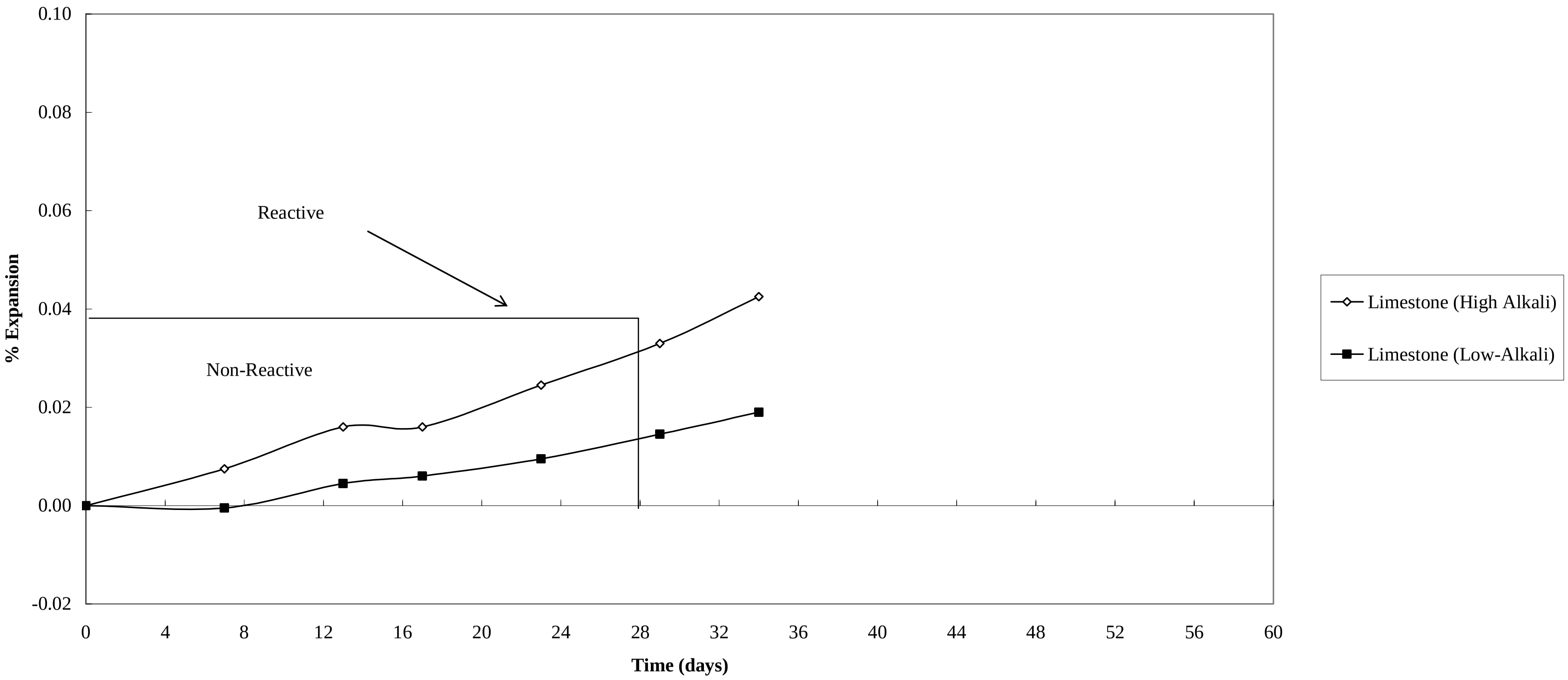


Figure 4-8: Expansion versus time for ASTM C 1260 (modified prism beam test) (natural blue rock and RCA with high alkali cement)

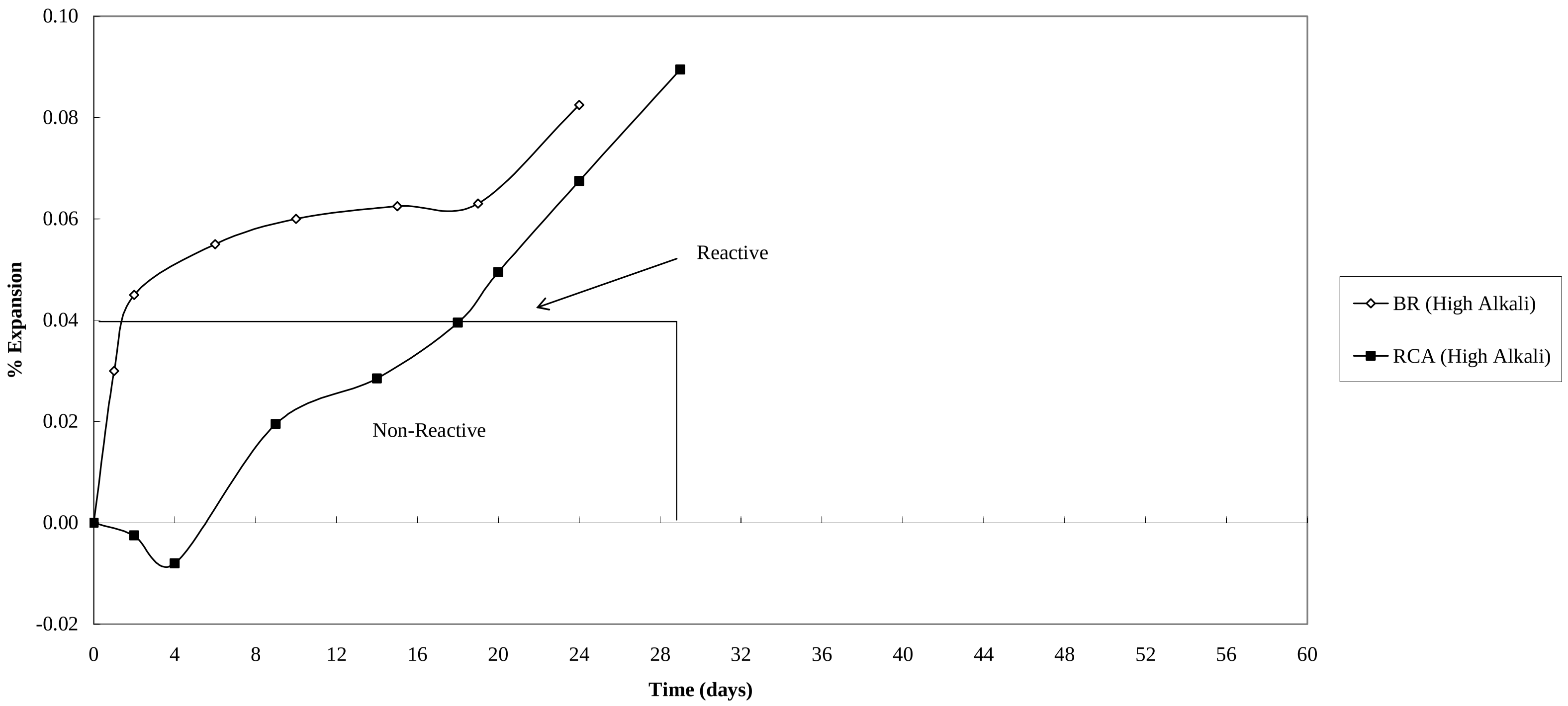


Figure 4-9: Expansion versus time for ASTM C 1260 (modified prism beam test) (natural blue rock and RCA with class F fly ash)

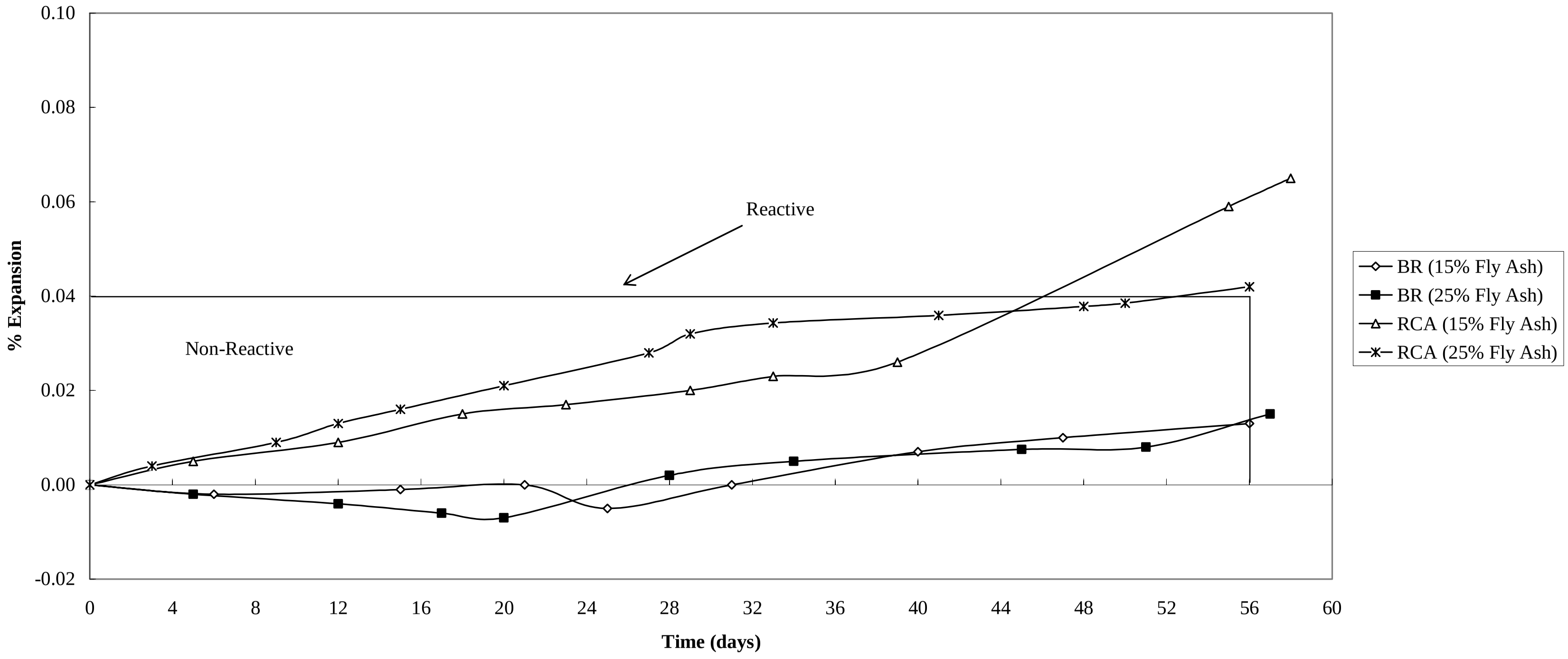


Figure 4-10: Expansion versus time for ASTM C 1260 (modified prism beam test)
(natural blue rock and RCA with GGBFS)

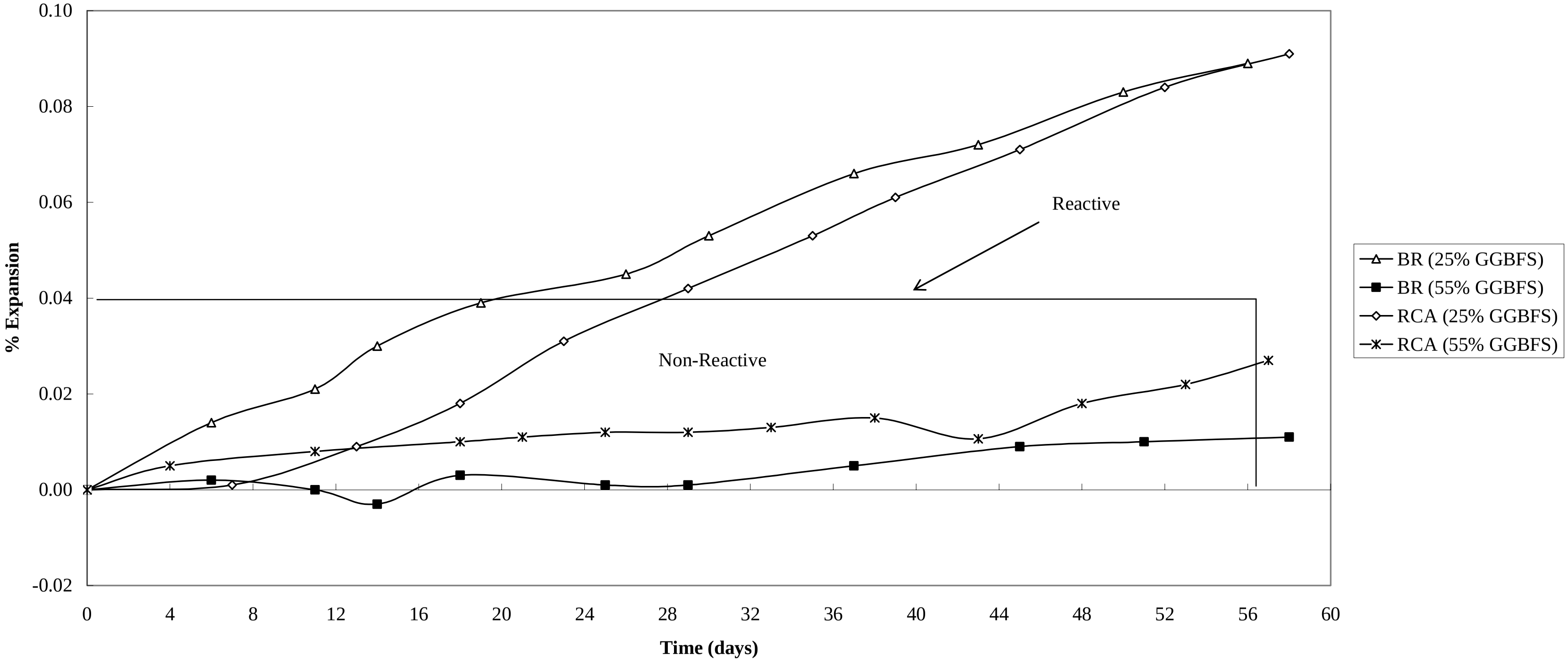


Figure 4-11: Expansion versus time for ASTM C 1260 (modified prism beam test)
(natural blue rock and RCA with lithium nitrate)

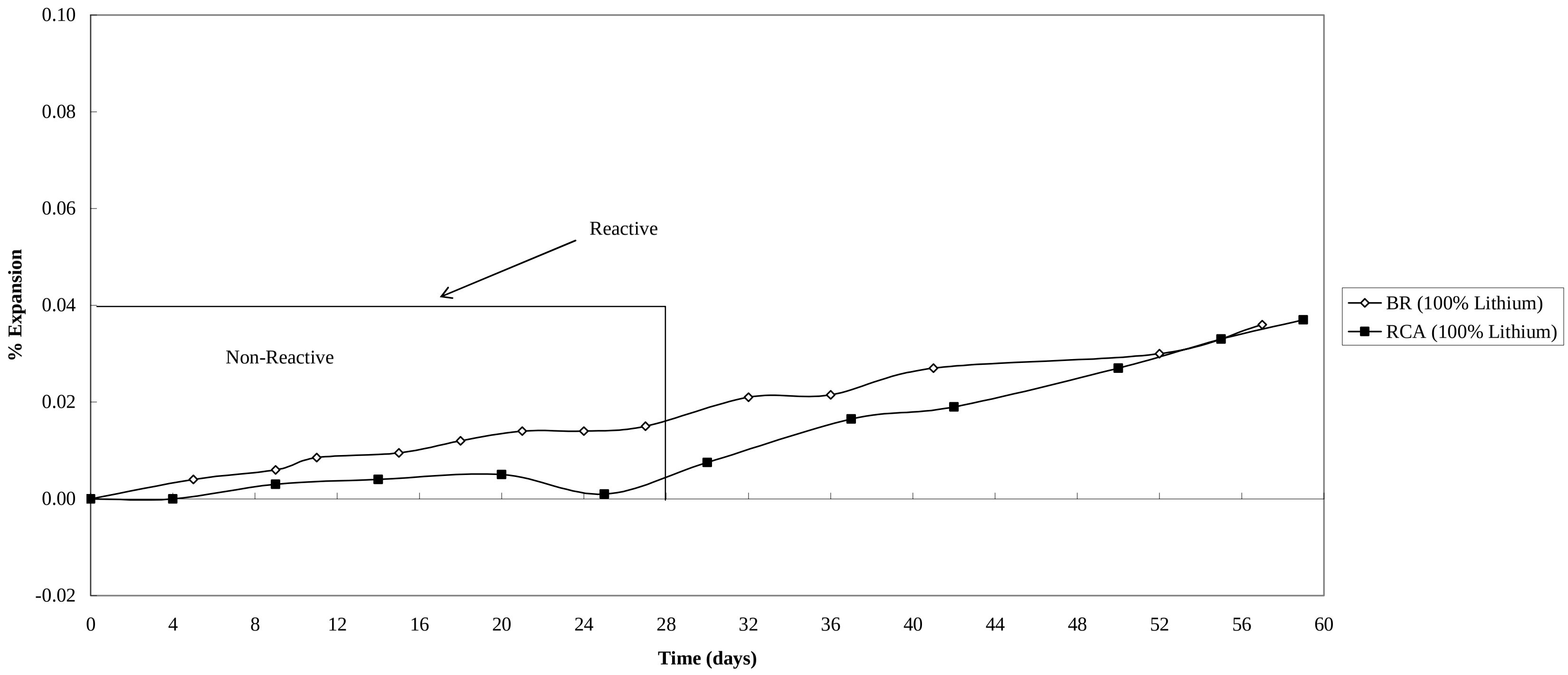
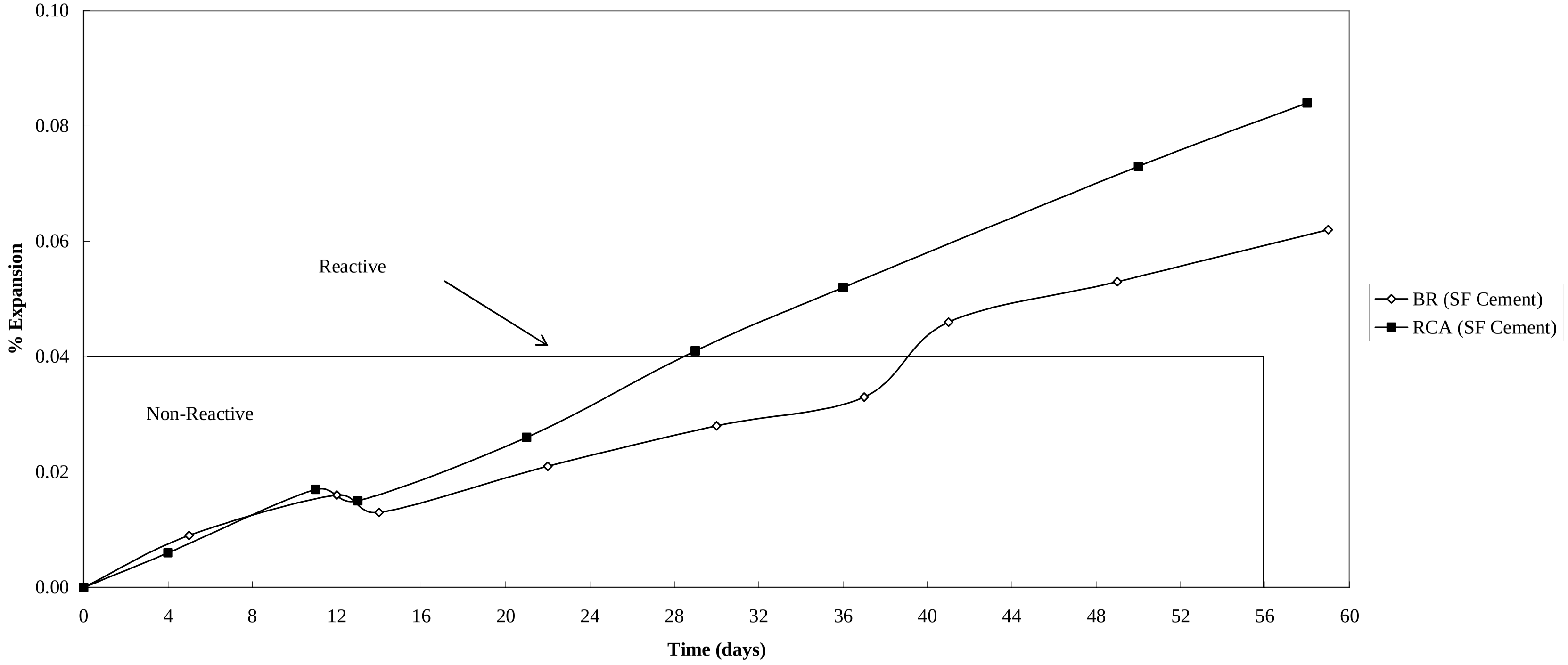


Figure 4-12: Expansion versus time for ASTM C 1260 (modified prism beam test) (natural blue rock and RCA with silica fume)



Standard Testing Procedures

ASTM C 1293 (Standard Prism Beam)

Rapid testing data showed that 25% class F fly ash, 55% GGBFS, and 100% lithium nitrate control ASR expansions with natural blue rock aggregate concrete and 55% GGBFS and 100% lithium nitrate control ASR expansion with recycled blue rock aggregate concrete. These results need to be further evaluated by an accepted ASTM ASR test specification to verify data and investigate full-scale concrete mixtures, rather than just aggregate and mitigation strategy behavior. ASTM C 1293 standard prism beam testing was carried out on all PCC mixtures as presented in Figures 4-13 through 4-23. These results showed comparable data and show correlation to both rapid test results. Testing durations are established at one-year for unmitigated mixtures and two-years for mitigated mixtures. An expansion above 0.04% is considered an ASR reactive PCC.

This was the first test done where low alkali cement was evaluated to control ASR expansions, as the samples were not submerged in one-normal NaOH solution. All preliminary ASTM C 1293 standard prism beam results show recycled concrete aggregate mixtures expanding from moisture unlike during the initial hydration period. This problem was investigated in detail and further adjustments were made to lower the premature expansion that will be discussed later in this section.

Figure 4-13 shows expansion results for natural and recycled blue rock aggregate with high and low alkali cement. It was observed that both aggregate sources, natural and recycled, showed non-reactive ASR expansion with low alkali cement as expansion levels were less than 0.04%. Both aggregate sources showed reactive ASR expansion with high alkali cement as expansion levels were over 0.04%. These results initially show that the aggregate sources in question are susceptible to ASR distress if proper mitigation strategies are not incorporated. Similar results were observed from ASTM C 1260 mortar-bar and prism beam testing, which showed good correlation between rapid ASR testing results.

Figure 4-14 shows expansion results for natural and recycled blue rock aggregate with low and high class F fly ash mitigations. Class F fly ash mitigation controlled ASR expansion below 0.04% for natural blue rock with 25% mitigation only. All other mixtures allowed expansion levels to exceed 0.04%, showing reactive behavior with ASR expansion. These results were similar to ASTM C 1260 mortar-bar and prism beam testing.

Figure 4-15 shows expansion results for natural and recycled blue rock aggregate with low and high GGBFS mitigations. The low mitigation did not control ASR expansion below 0.04% for either aggregate. The high mitigation controlled ASR expansion levels with natural blue rock aggregate, but not for recycled blue rock aggregate. These results are consistent with ASTM C 1260 mortar-bar and prism beam results for natural blue rock samples, but not for recycled blue rock samples.

Figure 4-16 shows expansion results for natural and recycled blue rock aggregate with 100% lithium nitrate mitigation. Lithium nitrate mitigation showed control over ASR expansion with natural blue rock, but not recycled blue rock. These results are consistent with ASTM C 1260 mortar-bar and prism beam results for natural blue rock aggregate samples, but not for recycled blue rock samples.

Figure 4-17 shows expansion results for natural and recycled blue rock aggregate with 8% silica fume mitigation. Silica fume showed control over ASR expansion with natural blue rock, but not recycled blue rock. Results are not consistent with ASTM C 1260 mortar-bar and prism beam data as expansions had not previously been below limits for either aggregate source.

Figure 4-18 shows expansion results for limestone aggregate with high and low alkali cement. The aggregate showed non-reactive results with both cements as expansion levels were below 0.04%. Results are comparable to ASTM C 1260 mortar-bar and prism beam data as expansions were controlled with both cements. Limestone aggregate was not further tested with ASTM C 1260 and 1293 test results both showing non-reactive ASR characteristics.

Preliminary ASTM C 1293 standard prism beam testing showed comparable results for all natural blue rock aggregate concrete data with rapid test results, except for silica fume blended cement. Low alkali cement stopped ASR expansion with both aggregates and showed the best control over ASR distress out of all mitigation strategies.

Figure 4-13: Expansion versus time for ASTM C 1293 (standard prism beam test) (natural blue rock and RCA with high and low alkali cement)

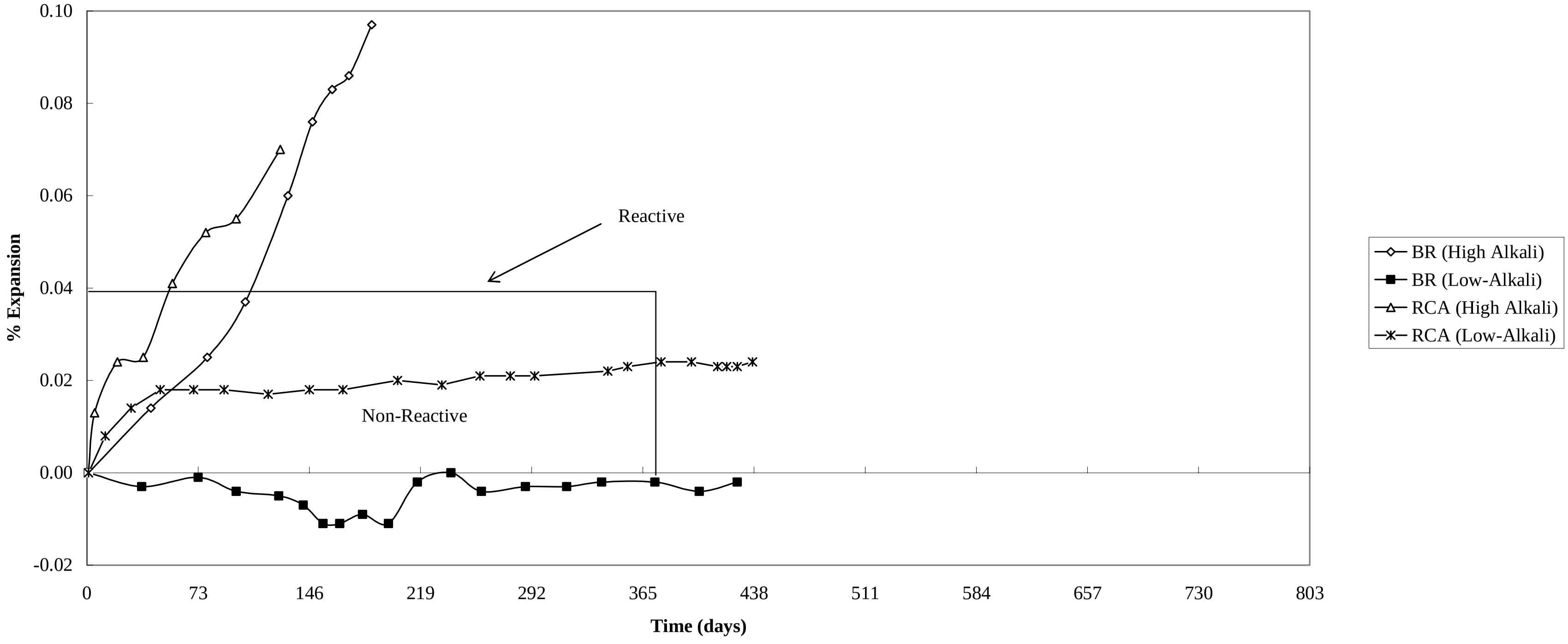
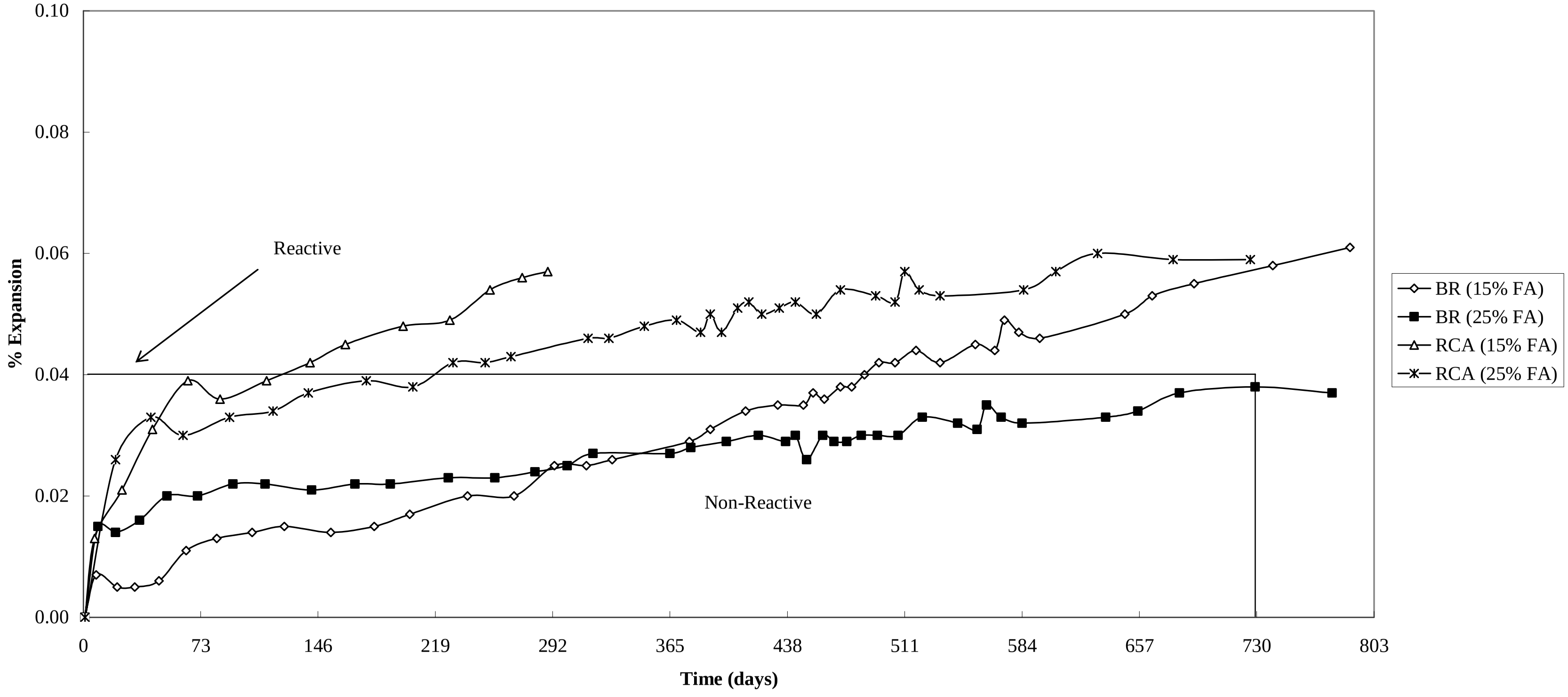


Figure 4-14: Expansion versus time for ASTM C 1293 (standard prism beam test)
(natural blue rock and RCA with class F fly ash)



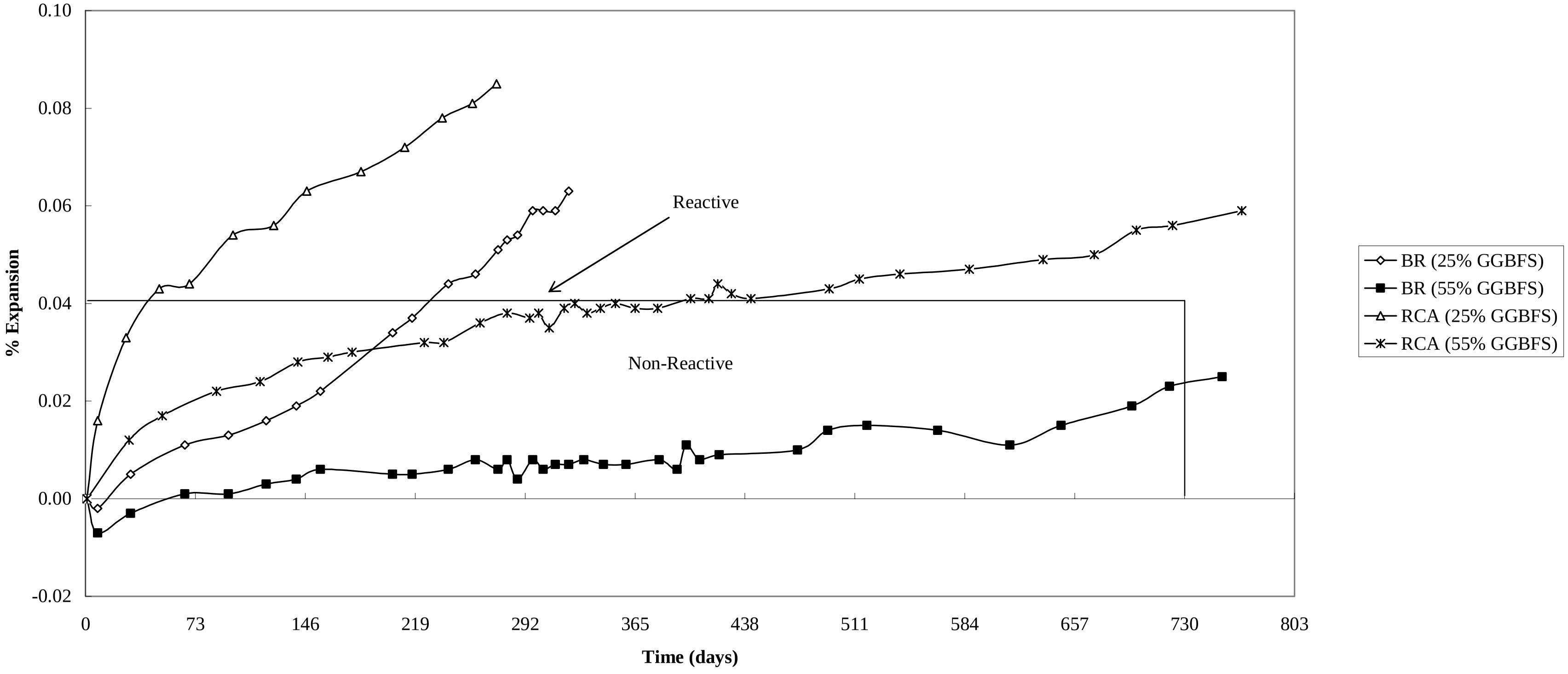


Figure 4-15: Expansion versus time for ASTM 1293 (standard prism beam test) (natural blue rock and RCA with GGBFS)

Figure 4- 16: Expansion versus time for ASTM C 1293 (standard prism beam test)
(natural blue rock and RCA with lithium nitrate)

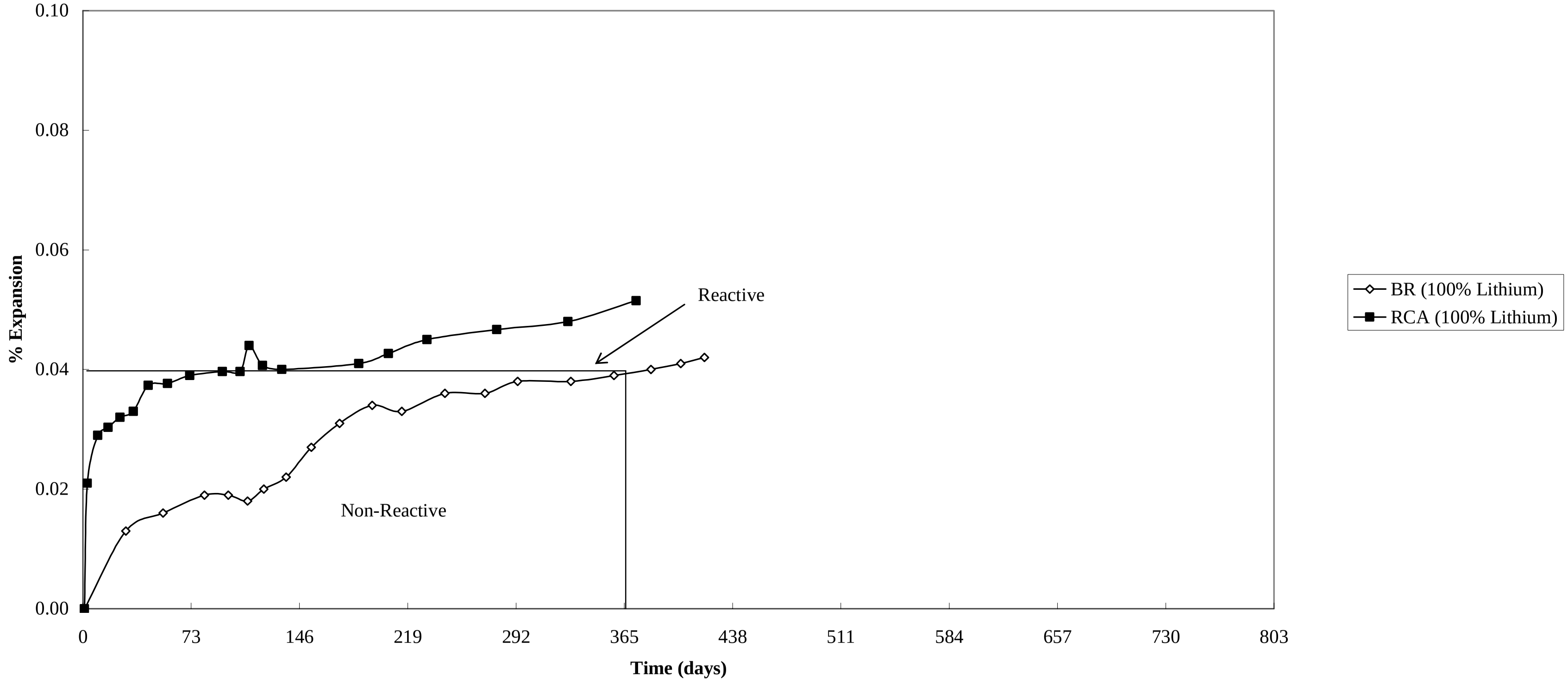


Figure 4-17: Expansion versus time for ASTM C 1293 (standard prism beam test)
(natural blue rock and RCA with silica fume)

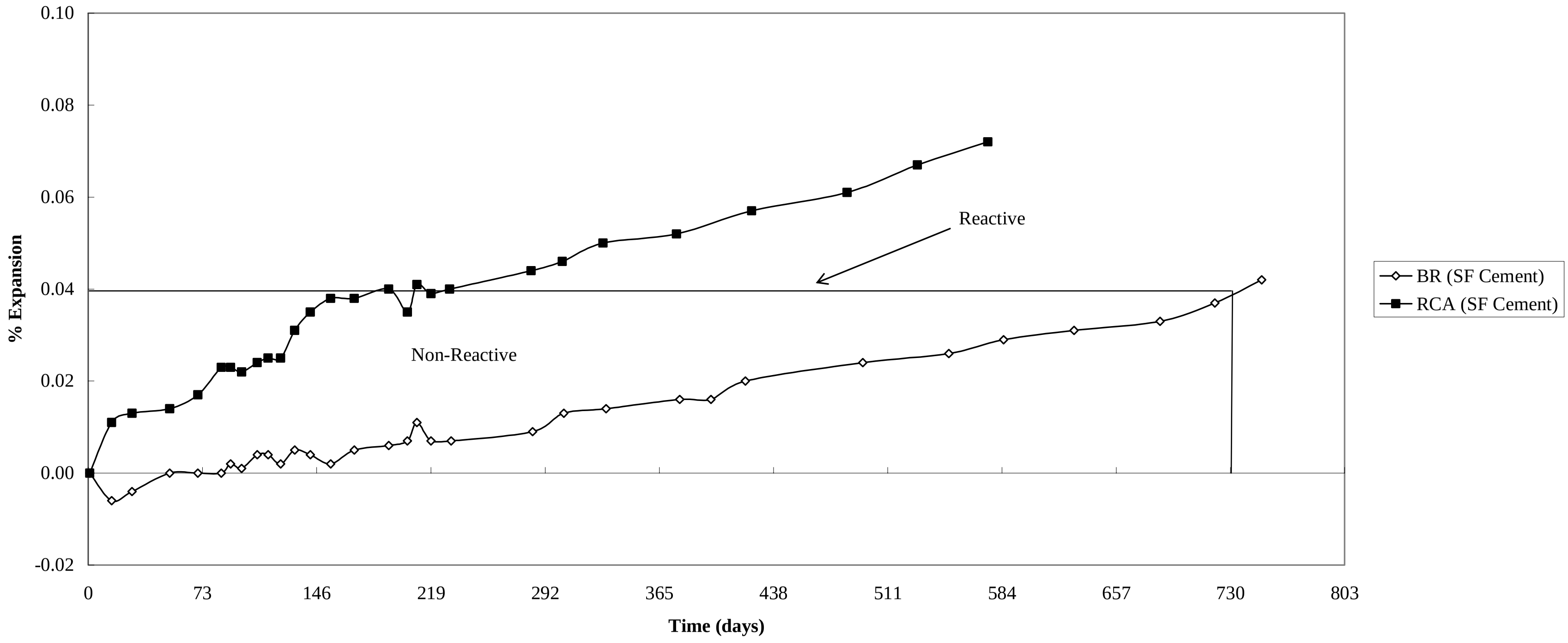
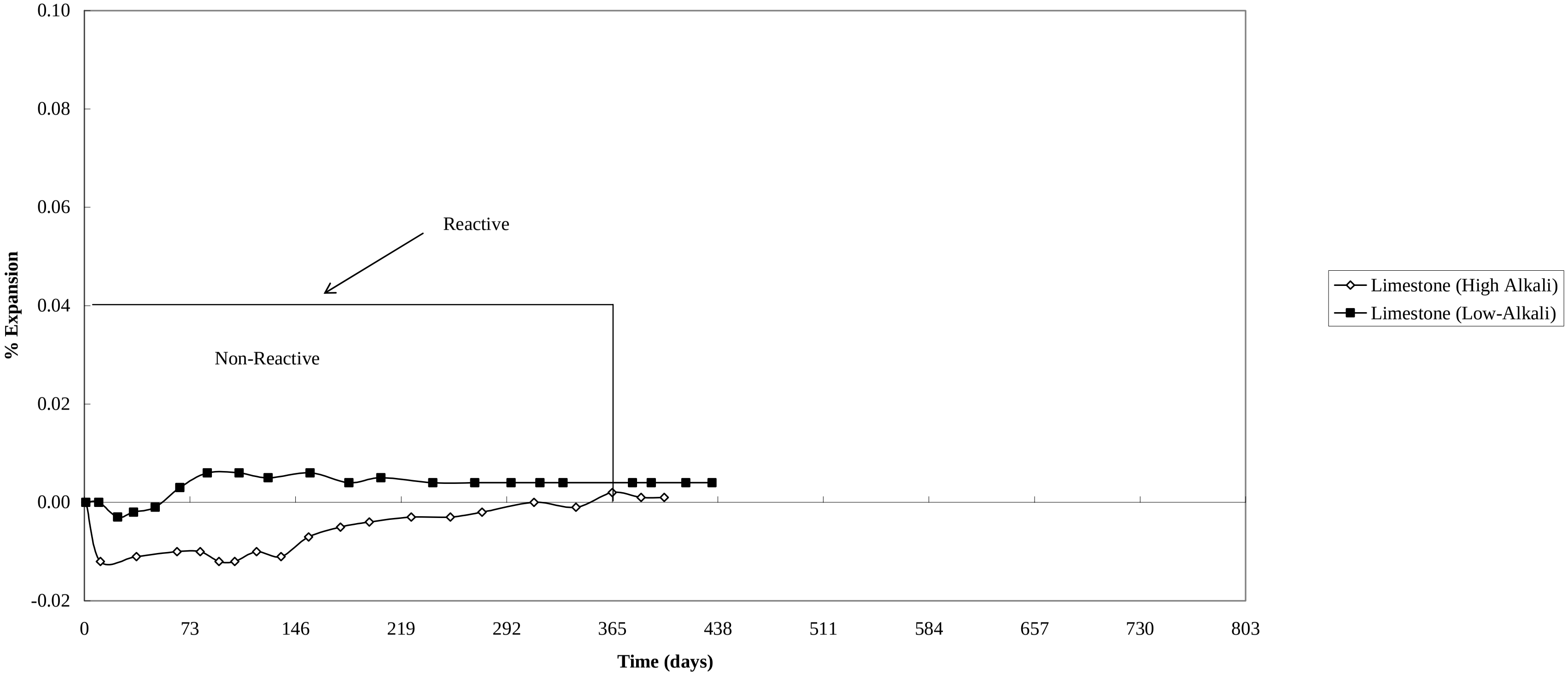


Figure 4-18: Expansion versus time for ASTM C 1293 (standard prism beam test) (limestone with high and low alkali cement)



All recycled aggregate concrete mixtures, except low-alkali mitigation, showed failures exceeding 0.04% expansion well before testing durations had terminated. This trend was not comparable with rapid test results with high mitigation GGBFS and 100% lithium nitrate mitigations controlling ASR expansion below acceptable limits. It was concluded that recycled aggregate concrete showed high initial expansions from water absorption during early age hydration as recycled aggregate material showed ten times the absorption capability to natural blue rock aggregate.

To overcome this problem all recycled aggregate mixtures were done over using pre-saturation techniques. Mixing the recycled aggregate concretes with pre-saturated aggregate, thus having aggregate pores filled with water (saturated surface dry state), would prevent mix water from entering empty aggregate pores and external water moving into the fresh concrete during early hydration. The initial rush of water into recycled aggregate pores provided expansive behavior showing false ASR expansion and terminating the ASTM C 1293 standard prism beam testing at an early age.

One set of concrete mixtures was made with recycled aggregate, for a particular PCC mixture, soaking in mix water for a forty-eight hour period. This was done with the mixture mixing water so free alkali would not escape the aggregate and be dismissed from the PCC mixture. The water level was above all aggregate to ensure complete saturation. A second set of mixtures was done with aggregates being vacuum saturated; again with each mixtures mix water and appropriate aggregate content. The vacuum was applied to the aggregate until visible air bubbles had stopped exiting the aggregate pores. It was assumed that if the pores were filled with water the early expansion would be eliminated.

ASTM C 1293 (Standard Prism Beam) w/ saturation techniques

Pre-saturation techniques were done with recycled aggregate concretes in which ASR mitigation strategies had showed potential to control ASR distress using ASTM C 1260 and 1293 procedures. All recycled aggregate mixtures, with pre-saturated aggregate, showed lower early expansions than preliminary ASTM C 1293 standard prism beam mixtures.

Figure 4-19 shows comparisons for recycled aggregate and high alkali cement pre-saturation mixtures. The preliminary mixture results and both saturation technique results are represented for the recycled aggregate mixture. Initial expansions are less for the saturated aggregate mixtures as predicted. The recycled aggregate mixture shows ASR expansion failures, which is consistent with all previous testing results.

Figure 4-20 shows comparisons for recycled aggregate and high class F fly ash mitigation pre-saturation mixtures. Both saturated aggregate mixtures have expansions less than 0.04%, thus fulfilling the criteria as a non ASR-reactive mixture. Saturation procedures dropped initial expansion from greater than 0.03% to less than 0.01% in the same forty-day interval. These results are consistent with previous testing as the high mitigation class F fly ash controlled expansions with natural blue rock and now with recycled blue rock mixtures.

Figure 4-21 shows that pre-saturated mixtures with high GGBFS mitigation did not show the same expansion decreases as the high alkali and class F fly ash mixtures. All mixtures showed expansions greater than 0.04%. GGBFS may show lower initial expansion than other mixtures as it does not contribute as much soluble alkali to a concrete mixture that can increase the pH of pore solution and trigger ASR at a faster rate than the other mitigation strategies used in this study. These results are not consistent with previous testing as the high mitigation GGBFS showed control over ASR expansion in all other previous tests with natural aggregate blue rock mixtures.

Figure 4-22 shows pre-saturation data for 100% lithium nitrate mixtures. Initial expansion was observed, but lithium nitrate mitigation characteristics often show initial expansion and then expansion readings stabilize once the lithium nitrate admixture initiates control over the expansion mechanism. The pre-saturated mixtures have expansions less than 0.04%, thus fulfilling the criteria as a non ASR-reactive mixture. Initial expansion occurred with pre-saturated mixtures, but to a lesser extent than the preliminary mixture. These results are consistent with previous testing as the lithium nitrate mitigation controlled ASR expansions.

Figure 4-23 shows pre-saturated data for 8% silica fume blended cement mixtures The pre-saturated mixtures showed smaller initial expansion than for the preliminary mixture, but all expansions were greater than 0.04%. These results were consistent with ASTM C 1293 prism beam data as the silica fume does not control ASR expansion.

Pre-saturation techniques showed lower initial expansion for all recycled aggregate mitigation mixtures. The absorption characteristics of recycled aggregate was larger than that of natural aggregates and has been an issue since recycling PCC was first introduced.[4] Filling free water voids in recycled aggregate prevents initial expansion due to water absorption for recycled aggregate concrete mixtures during early hydration periods.

Figure 4-19: Expansion versus time for ASTM C 1293 (standard prism beam w/ saturation techniques) (RCA with high alkali cement)

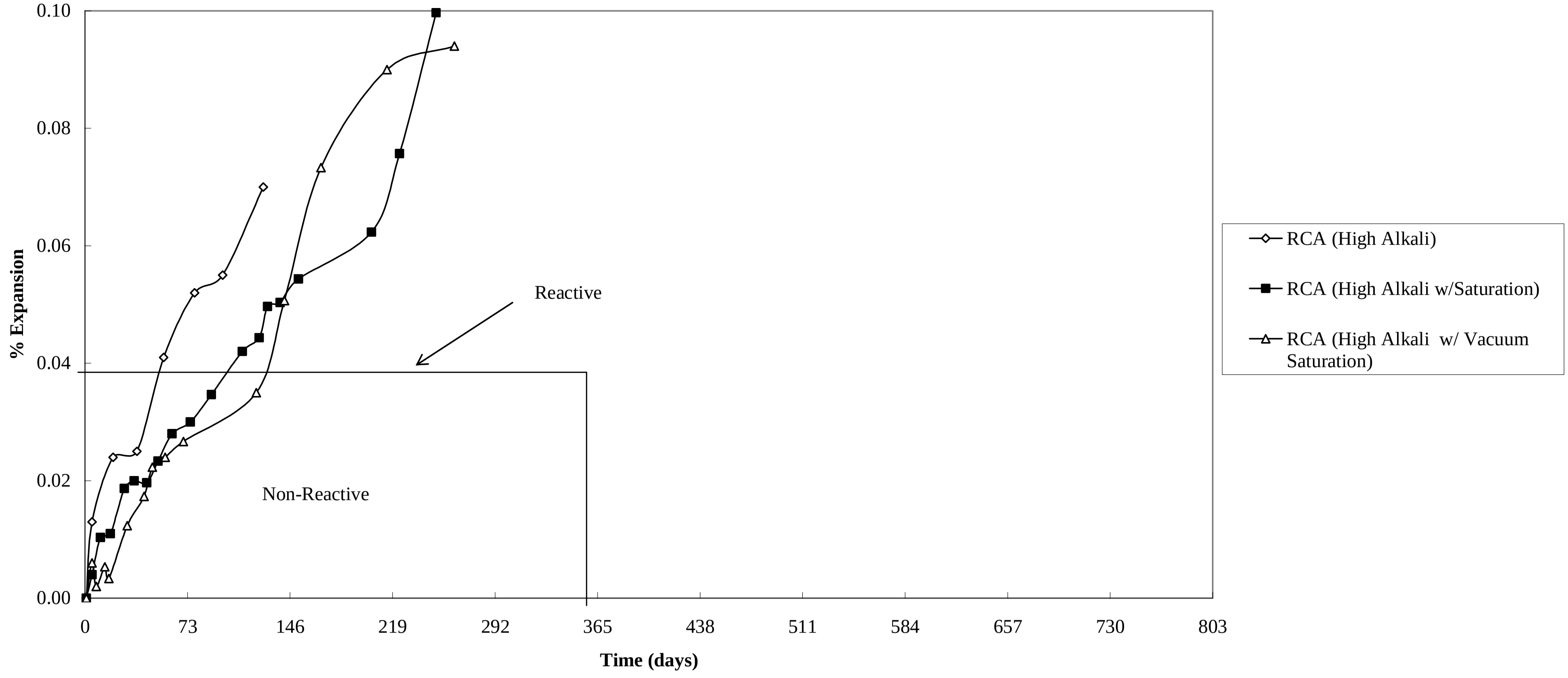


Figure 4-20: Expansion versus time for ASTM C 1293 (standard prism beam w/ saturation techniques)
(RCA with class F fly ash)

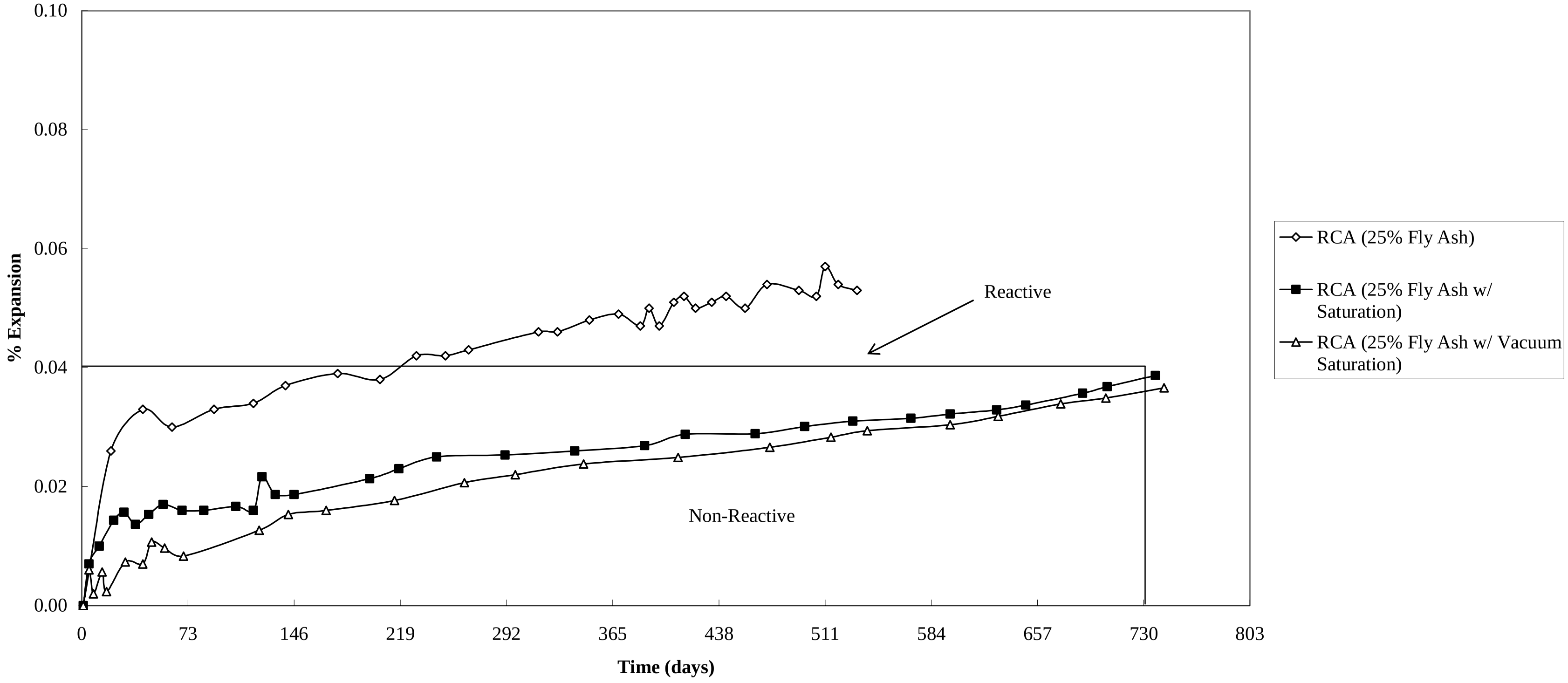


Figure 4-21: Expansion versus time for ASTM C 1293 (standard prism beam w/ saturation techniques) (RCA with GGBFS)

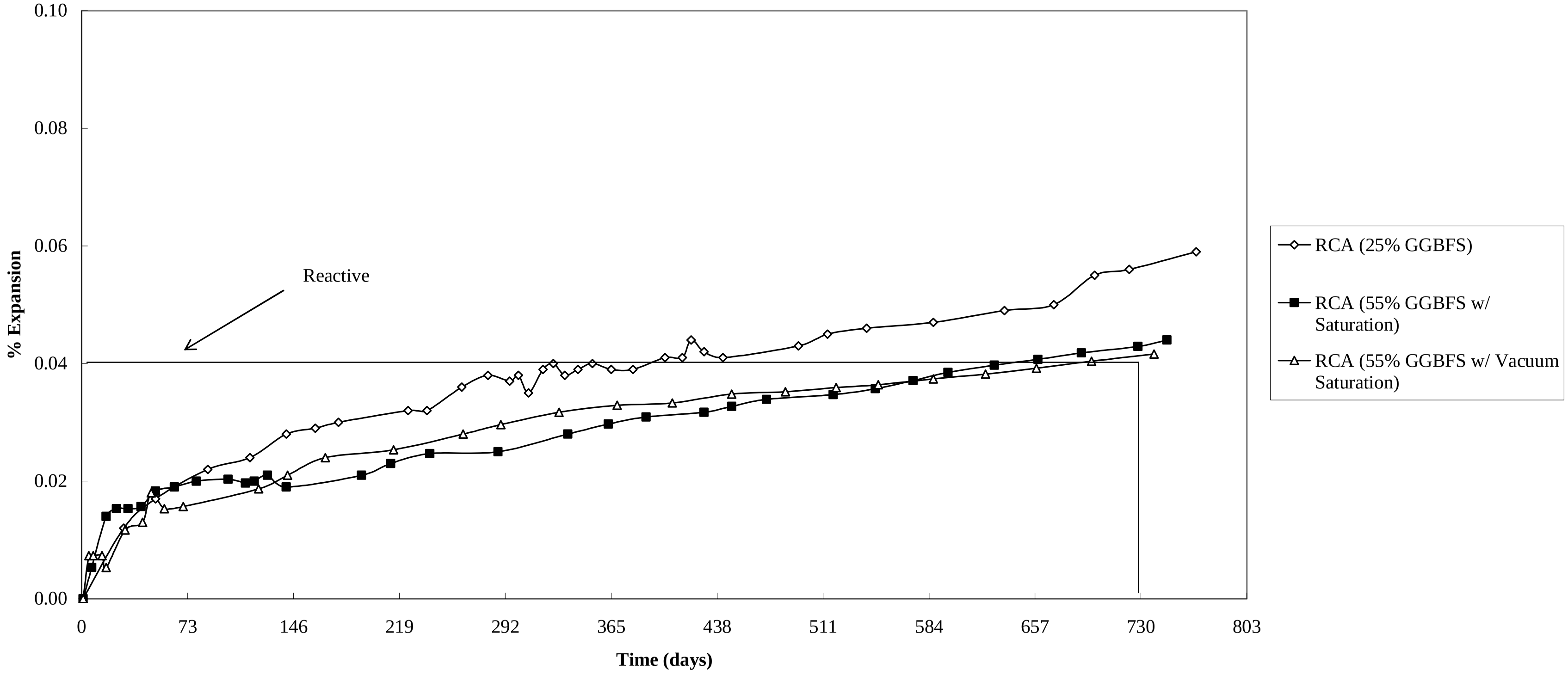


Figure 4-22: Expansion versus time for ASTM C 1293 (standard prism beam w/ saturation techniques) (RCA with lithium nitrate)

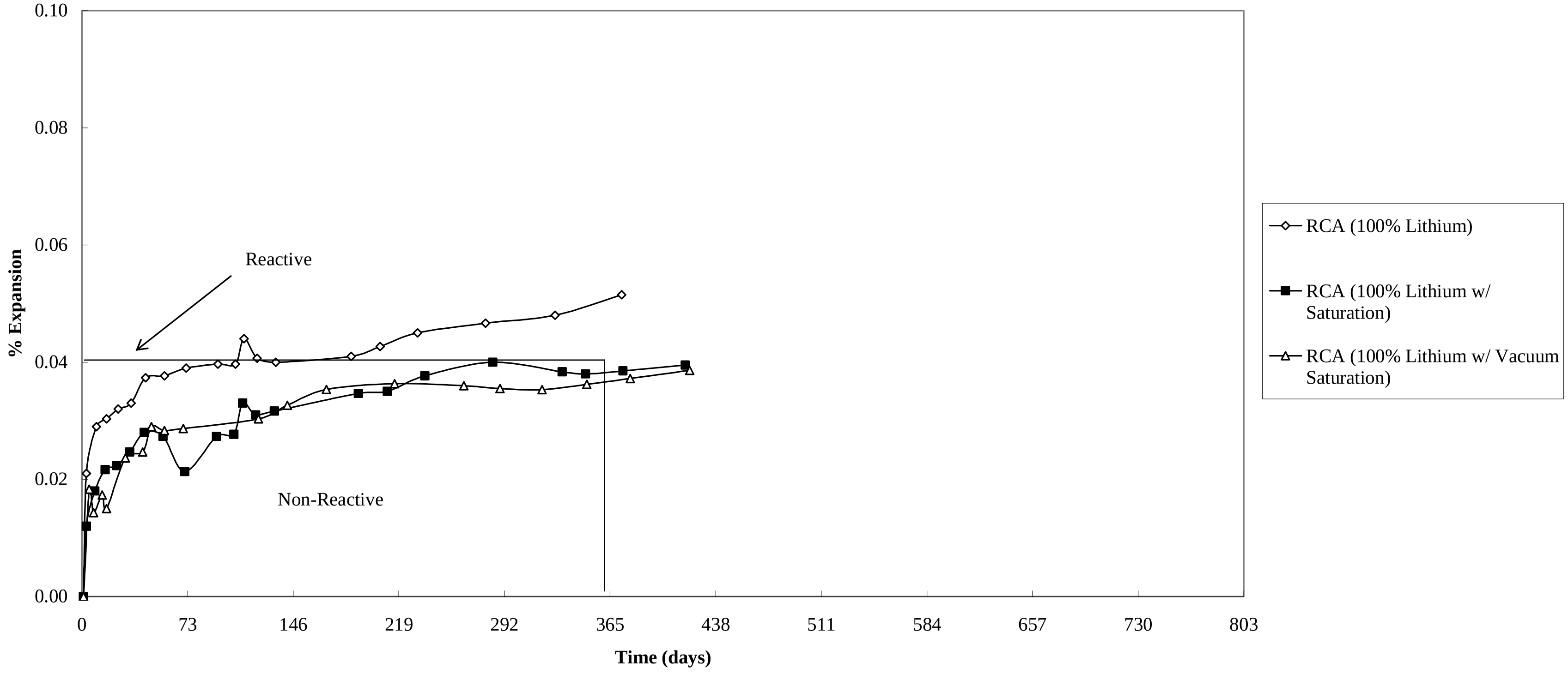
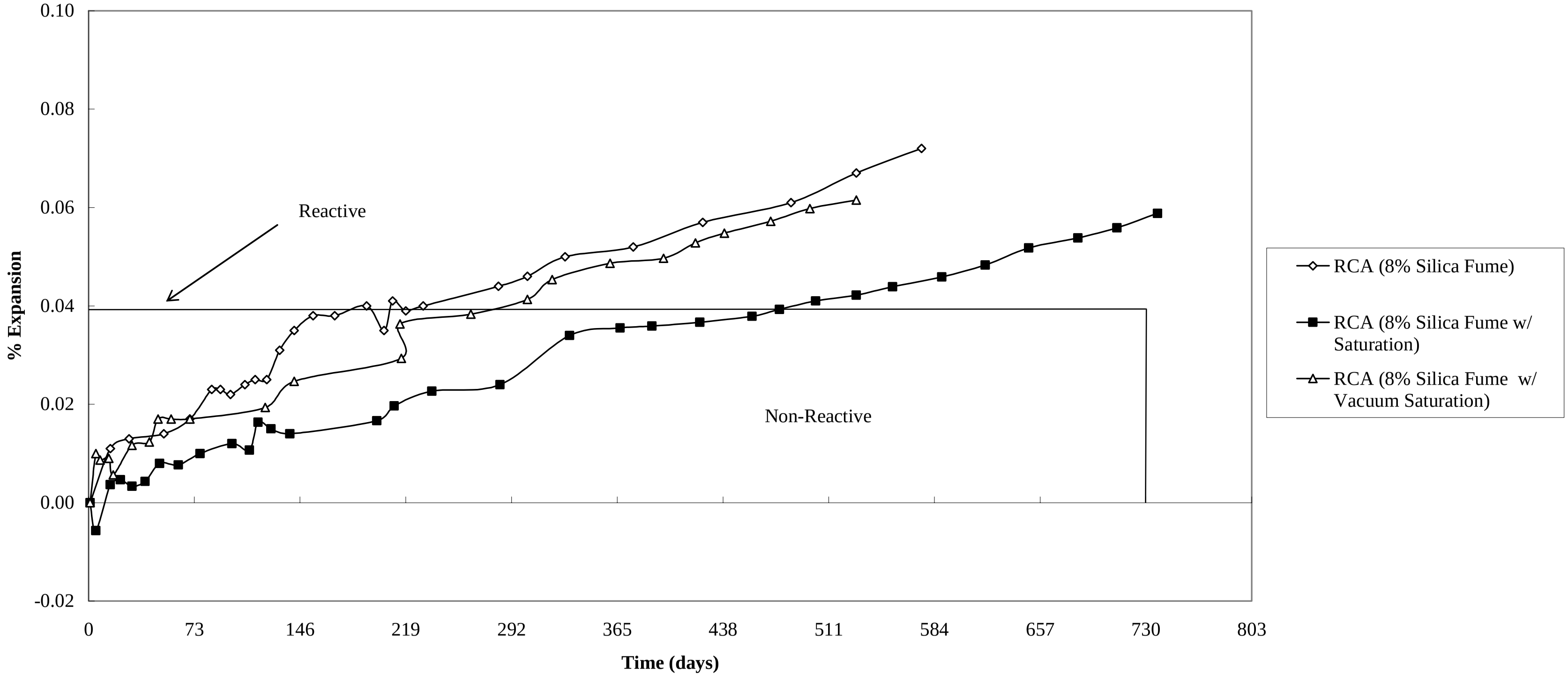


Figure 4-23: Expansion versus time for ASTM C 1293 (standard prism beam w/ saturation techniques)
(RCA with silica fume)



Modified Testing Procedures

ASTM C 1293 modified vacuum-sealed cubes with holes, ASTM C 1293 modified electrical cylinder testing, and ASTM C 1260 modified cubes with holes were the three modified ASR testing procedures used in this study that have been developed at the University of New Hampshire.[25] Past research done with ASTM C 1293 modified vacuum-sealed cubes with holes showed results obtained within fifty days as opposed to three hundred sixty five days or one hundred days as opposed to seven hundred thirty days for mixtures containing cement mitigations, for a 0.04% expansion. This shows a potential to gain results over six times as fast as with ASTM C 1293 standard prism beam testing.

Information on electrical cylinder and ASTM C 1260 modified cubes with holes testing is limited. Past results show ASR expansion can be accelerated, but no failure criteria has been established.[25]

The following results show that accelerated testing procedures show good correlation to accepted ASTM specifications for potential ASR test results.

Vacuum-Sealed Cubes (ASTM C 1293 Modification)

Testing was carried out on all PCC mixtures as presented in Figures 4-24 through 4-31.

Figure 4-24 shows expansion results for natural and recycled blue rock aggregate with high and low alkali cement. It was observed that both aggregate sources, natural and recycled, showed non-reactive ASR expansion with high and low alkali cement as expansion levels were less than 0.04%. These results contradict past data as high alkali concrete mixtures have shown reactive ASR behavior. ASTM C 1260 mortar-bar/modified prism beam and ASTM C 1293 standard prism beam tests showed both aggregates with high alkali cement to have reactive characteristics. Both low alkali concrete mixtures showed non-reactive ASR characteristics, which agreed with ASTM C 1260 mortar-bar/modified prism beam and ASTM C 1293 standard prism beam tests.

Figure 4-25 shows expansion results for natural and recycled blue rock aggregate with low and high class F fly ash mitigations. All mixtures show failures with expansions greater than 0.04%. These results are not similar to past testing data, as the natural blue rock expansions are not controlled. All other mixtures showed failures as expected without saturation treatment.

The recycled blue rock mixtures showed high early age expansions as seen with the recycled aggregate with the ASTM C 1293 prism beam results. This was investigated, as previously discussed, with saturation procedures done with the ASTM C 1293 prism beam testing. The recycled aggregate was saturated with the vacuum-sealed process only, as this process showed the best results to control early age expansions.

Figure 4-26 shows high class F fly ash mitigation with saturated recycled aggregate concrete. The saturated mixture shows expansion failure exceeding 0.04%. The saturated recycled aggregate mixture shows initial expansion, but almost half that of the original mix of 0.04% at 15 days compared to 0.07% at 15 days. This pattern was seen with ASTM C 1293 prism beam saturation procedures as expansions dropped significantly.

Figure 4-27 shows expansion results for natural and recycled blue rock aggregate with low and high GGBFS mitigations. All mixtures show failures with expansions greater than 0.04% at one hundred days. These results are not similar to past testing data, as the natural blue rock expansions are not controlled with the high mitigation. All other mixtures showed failures as expected.

Figure 4-28 shows high GGBFS mitigation with saturated natural and recycled aggregate concrete. The saturated mixtures show expansion failure, exceeding 0.04%. The saturated recycled aggregate mixture shows initial expansion, but almost half that of the original mix of 0.02% at 30 days compared to 0.04% at 30 days. This pattern was seen with ASTM C 1293 prism beam saturation procedures as expansions dropped significantly.

This decrease in early age expansion, as seen with the class F fly ash and GGBFS saturated mixtures, defends the hypothesis that high initial expansion with recycled aggregate mixtures was caused by moisture absorption after free water pores were filled during early hydration. The concrete system, aggregate and cement matrix, came to an equilibrium state and all remaining expansion was characterized through the ASR mechanism.

Figure 4-29 shows expansion results for natural and recycled blue rock aggregate with 100% lithium nitrate mitigation. Lithium nitrate mitigation showed control over ASR expansion with expansion less than 0.04%. These results are consistent with ASTM C 1260 mortar-bar/prism beam and ASTM C 1293 prism beam results with the 100% mitigation controlling expansion below allowable test limits. Saturated cube samples were not done with lithium nitrate mitigation for recycled aggregate, as results showed non-reactive characteristics without the procedure.

Figure 4-30 shows expansion results for natural and recycled blue rock aggregate with 8% silica fume mitigation. Silica fume showed control over ASR expansion with natural blue rock, but expansions were just over 0.04% for the recycled blue rock mixture. Results are consistent with previous ASTM C 1293 prism beam testing data as expansions were controlled with natural blue rock mixtures.

Figure 4-31 shows silica fume blended cement results with saturated recycled blue rock aggregate. Results showed that saturated recycled aggregate concrete was below ASR potential expansion limits. This result is not consistent with previous data as no other testing has shown the silica fume mitigation to control expansions below failure limits with the recycled aggregate.

All vacuum-sealed cube with hole samples showed higher variation as samples were measured. This has a direct relationship to the increase surface-area to volume ratio relationship compared to a standard prism beam sample. Comparable results were seen with all samples, compared to published ASTM testing data, except for both high alkali samples, high mitigation GGBFS and 8% silica fume samples. Modified ASTM C 1293 vacuum-sealed cube with hole samples showed potential as a rapid testing procedure to gain faster results with ASR potential characterization. Failure criteria, 0.04% expansion at fifty or one hundred days, showed good correlation to results from established ASTM C 1293 prism beam testing at three hundred sixty five days or seven hundred thirty days.

Figure 4-24: Expansion versus time for vacuum-sealed cubes (ASTM C 1293 modification) (natural blue rock and RCA with high and low alkali cement)

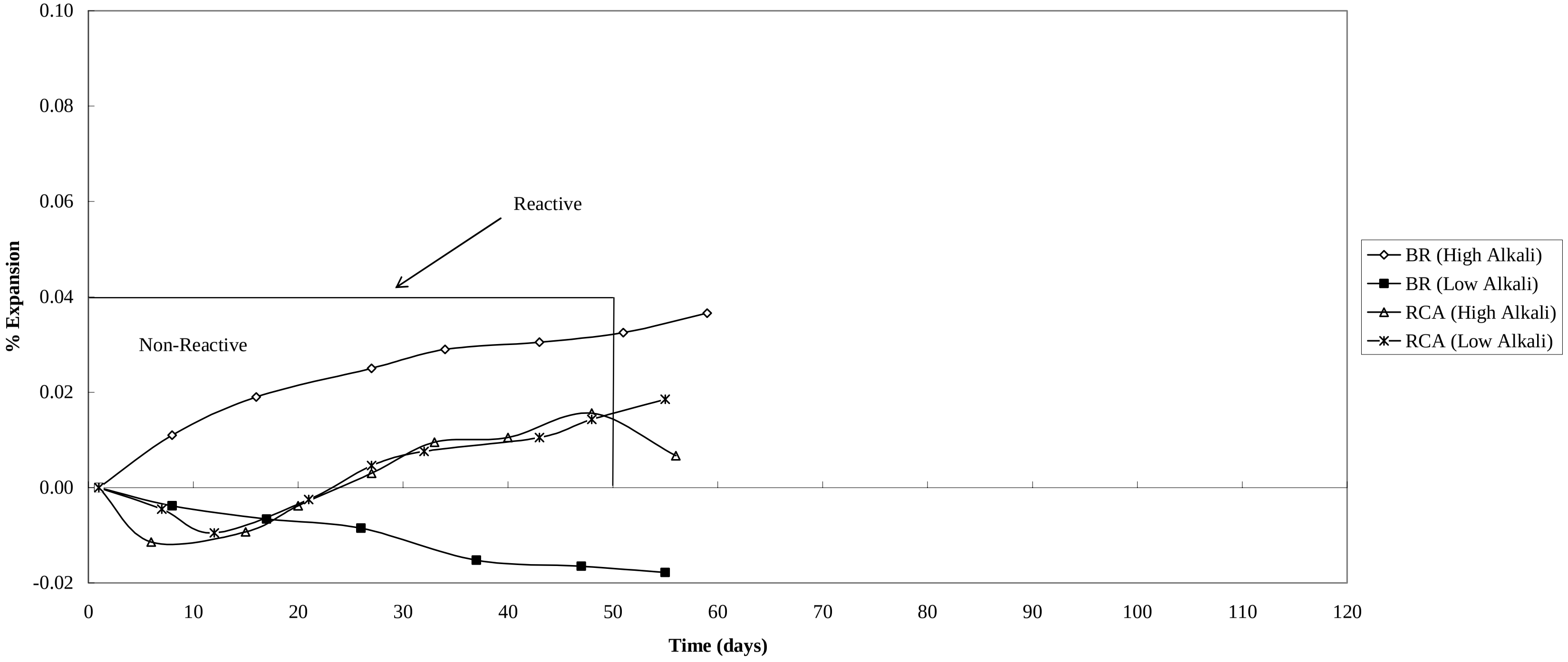


Figure 4-25: Expansion versus time for vacuum-sealed cubes (ASTM C 1293 modification)
(natural blue rock and RCA with class F fly ash)

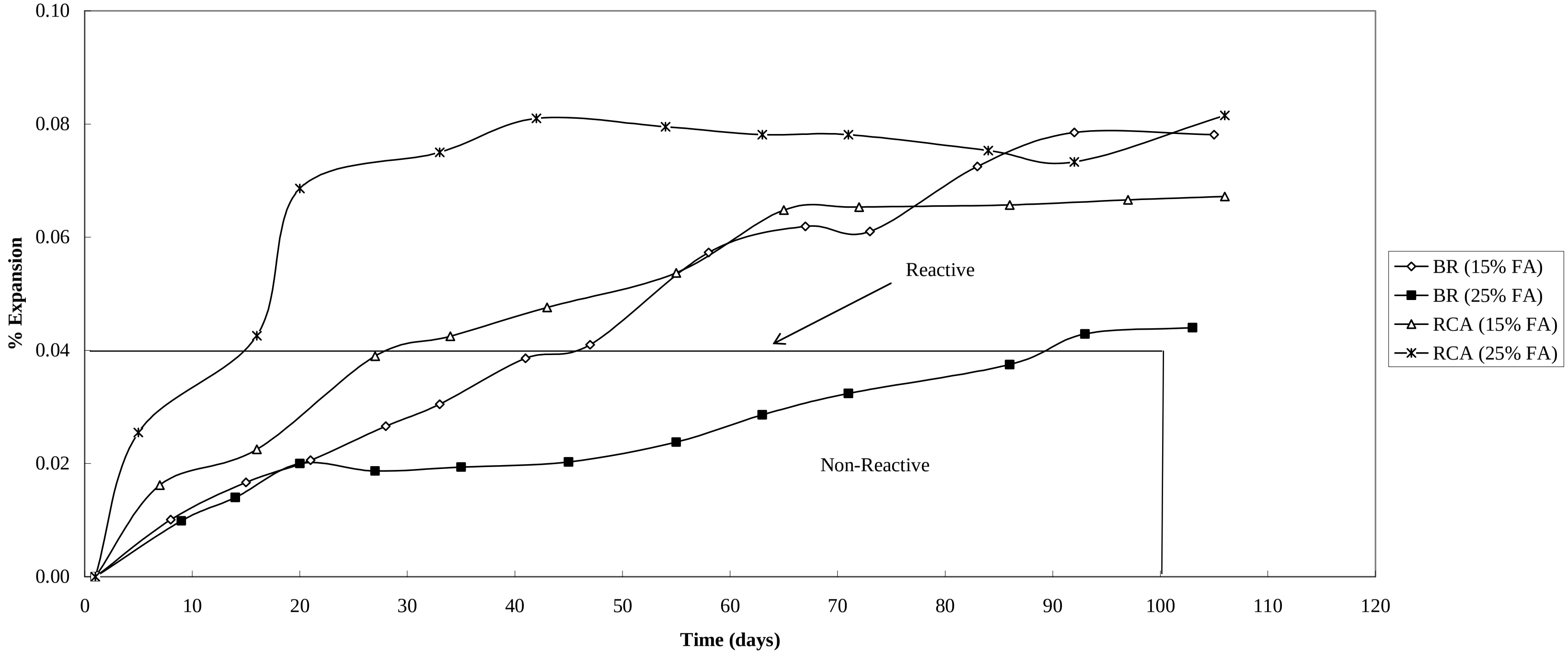


Figure 4-26: Expansion versus time for vacuum-sealed cubes (ASTM C 1293 modification w/ saturation techniques)
(RCA with class F fly ash)

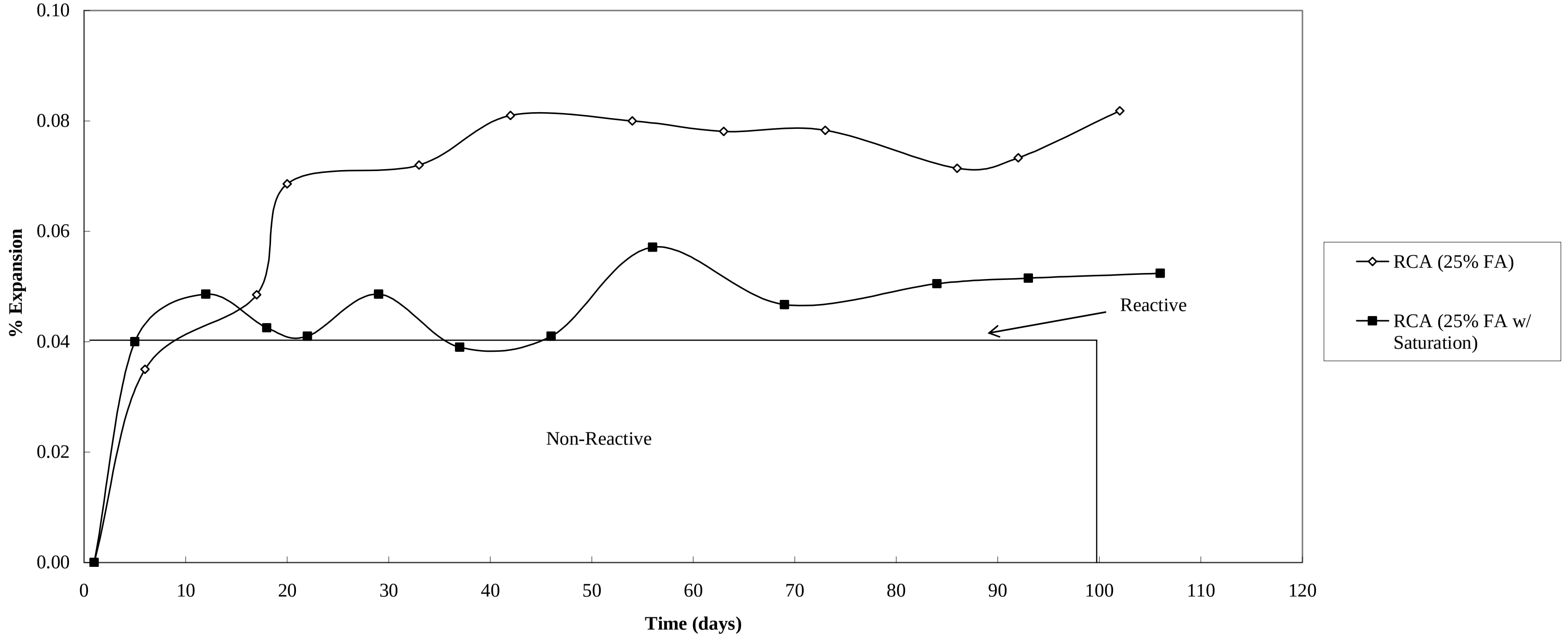


Figure 4-27: Expansion versus time for vacuum-sealed cubes (ASTM C 1293 modification) (natural blue rock and RCA with GGBFS)

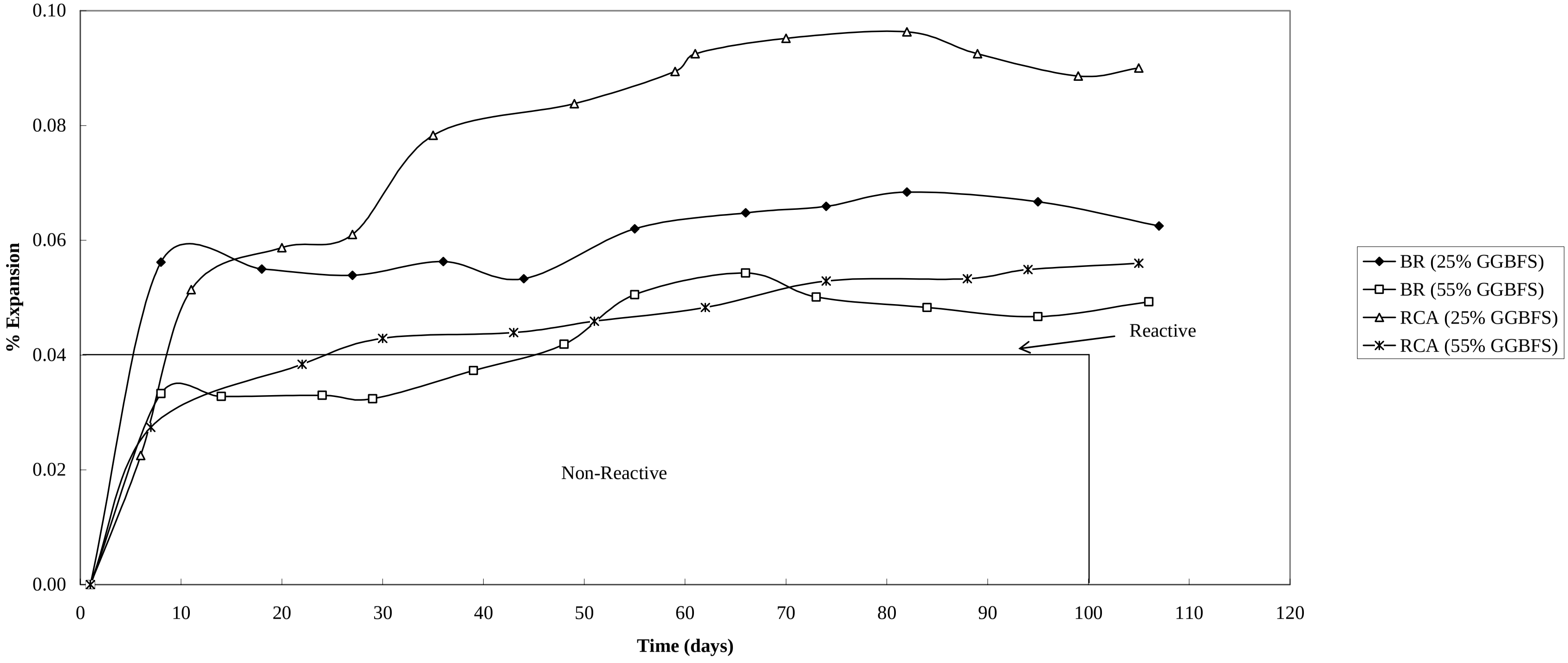


Figure 4-28: Expansion versus time for vacuum-sealed cubes (ASTM C 1293 modification w/ saturation techniques) (RCA with GGBFS)

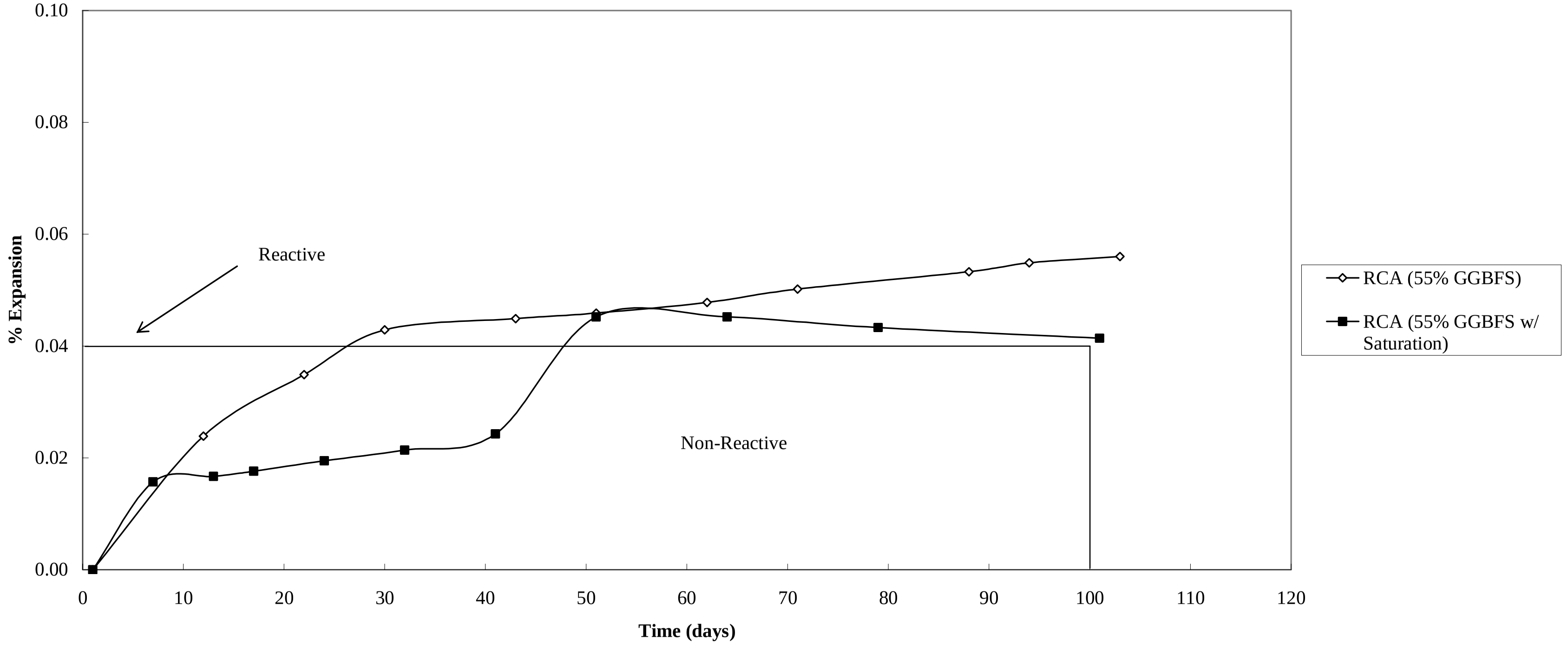


Figure 4-29: Expansion versus time for vacuum-sealed cubes (ASTM C 1293 modification) (natural blue rock and RCA with lithium nitrate)

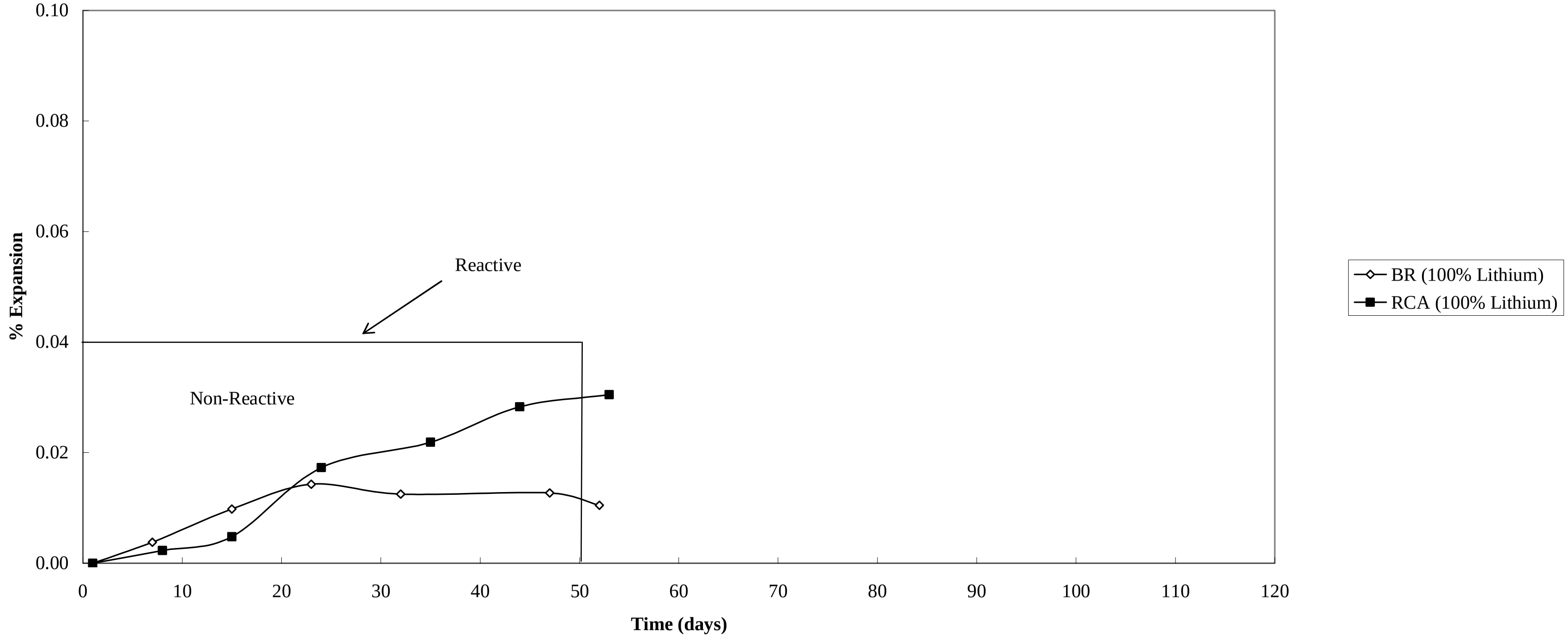


Figure 4-30: Expansion versus time for vacuum-sealed cubes (ASTM C 1293 modification) (natural blue rock and RCA with silica fume)

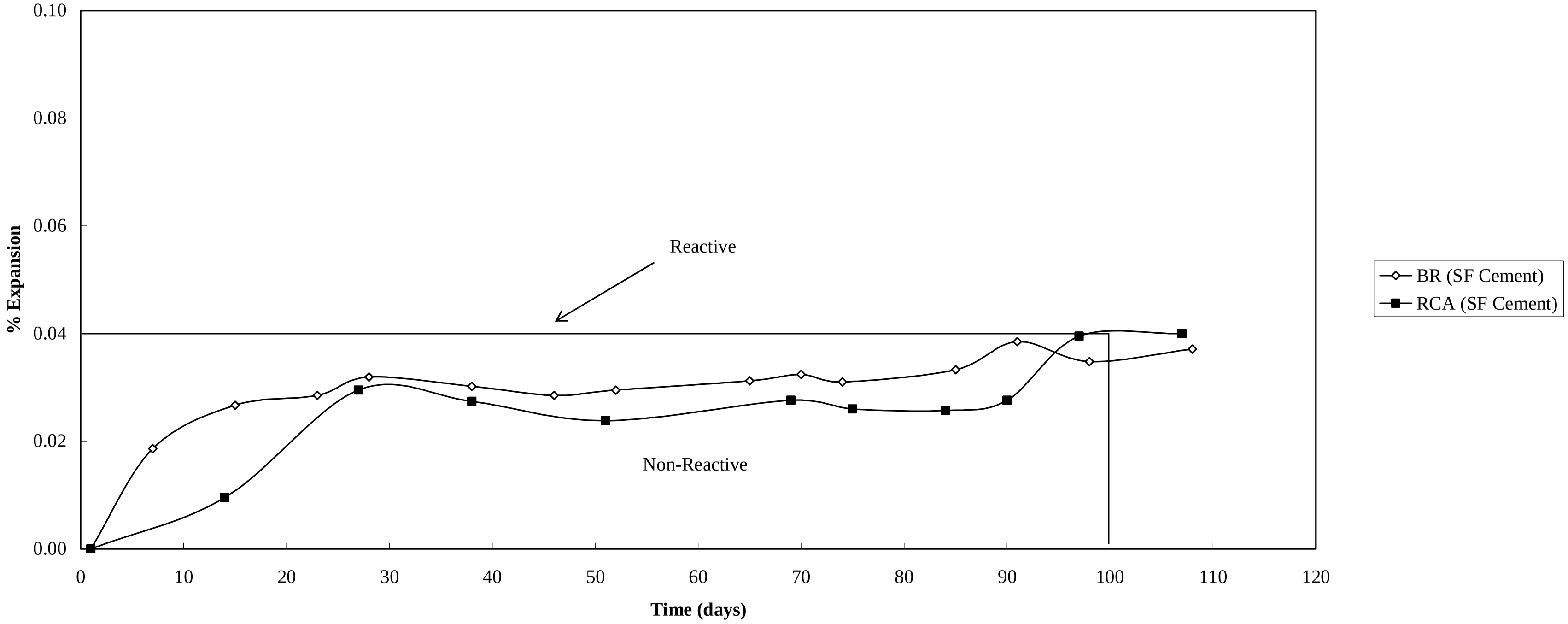
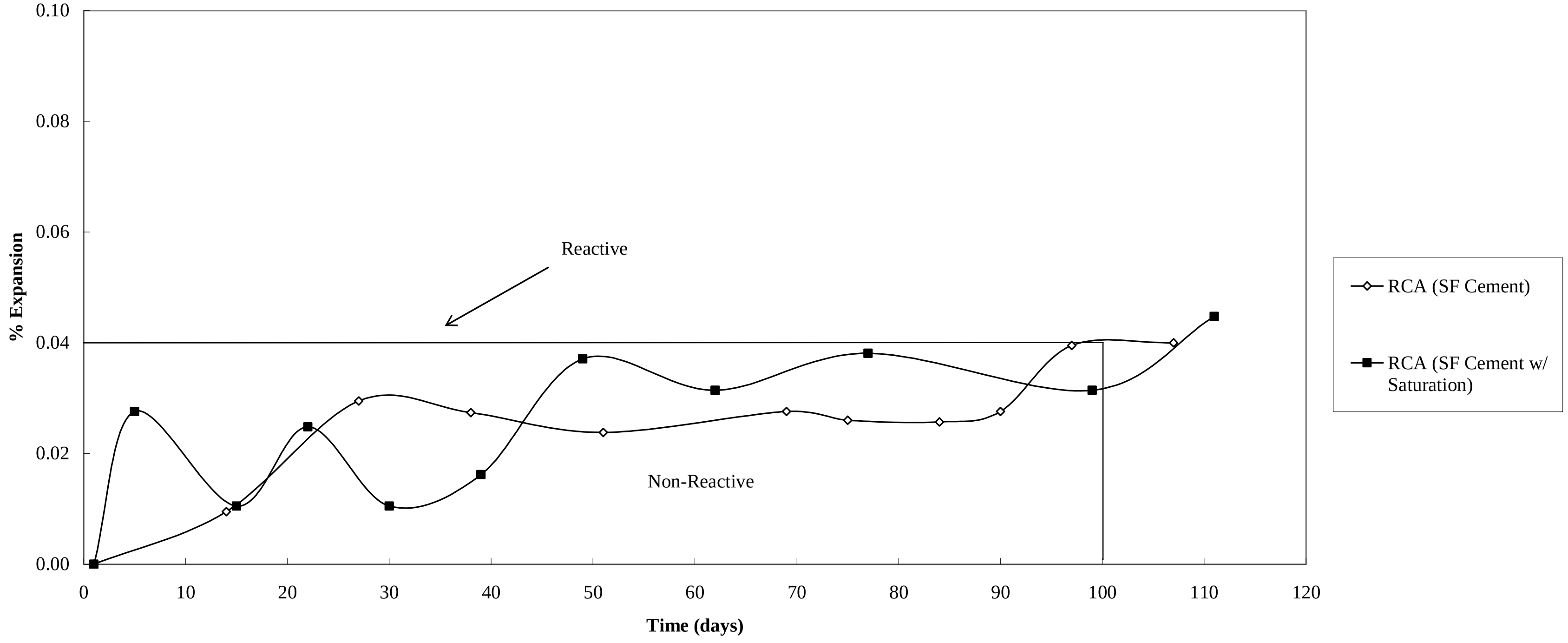


Figure 3-31: Expansion versus time for vacuum-sealed cubes (ASTM C 1293 modification w/ saturation techniques) (RCA with silica fume)



Electrical Cylinders (ASTM C 1293 Modification)

In all cases, it was observed that electrical current introduction increased sample expansion than with ASTM C 1293 standard prism beam testing. RCA mixtures were not tested with aggregate saturation techniques as this test was run to observe increased expansion behavior, not the ability of mitigation techniques to control ASR expansion. Testing was carried out on all PCC mixtures as presented in Figures 4-32 through 4-41.

Figures 4-32 and 4-33 shows expansion results for natural and recycled blue rock aggregate mixtures with high and low alkali cements. It was shown in both cases that electrical cylinder samples expanded at a faster rate than ASTM C 1293 prism beam samples, with the exception of the natural blue rock aggregate with high alkali cement. Natural and recycled blue rock aggregate mixtures showed a comparable expansion rate with both testing procedures. It was observed that low alkali cement was the only mitigation strategy able to control ASR distress with RCA mixtures using electrical current testing, further showing that it is the most effective mitigation strategy used in this study to control ASR distress.

Figures 4-34 and 4-35 shows expansion results for natural and recycled blue rock aggregate mixtures with low and high class F fly ash mitigations. It was shown in both cases that electrical cylinder samples expanded at a faster rate than ASTM C 1293 prism beam samples. Natural and recycled blue rock aggregate mixtures showed a comparable expansion rate with both testing procedures.

Figures 4-36 and 4-37 shows expansion results for natural and recycled blue rock aggregate mixtures with low and high GGBFS mitigations. It was shown in both cases that electrical cylinder samples expanded at a faster rate than ASTM C 1293 prism beam samples, with the exception of the natural blue rock aggregate with 25% GGBFS mitigation. Natural and recycled blue rock aggregate mixtures showed a comparable expansion rate with both testing procedures.

Figures 4-38 and 4-39 shows expansion results for natural and recycled blue rock aggregate mixtures with 100% lithium nitrate mitigation. It was shown in both cases that electrical cylinder samples expanded at a faster rate than ASTM C 1293 prism beam samples. Natural and recycled blue rock aggregate mixtures showed a comparable expansion rate with both testing procedures.

Figures 4-40 and 4-41 shows expansion results for natural and recycled blue rock aggregate mixtures with 8% silica fume mitigation. It was shown in both cases that electrical cylinder samples expanded at a faster rate than ASTM C 1293 prism beam samples. Natural and recycled blue rock aggregate mixtures showed a comparable expansion rate with both testing procedures.

Modified ASTM C 1293 electrical testing data showed higher rates of expansion than ASTM C 1293 standard prism beam expansion data. The results were positive as data showed ASR expansion rates can be increased, causing a decrease in testing duration to gain expansion data for ASR potential characterization. With all mixtures expanding faster with electrical current addition, the modified test was proven effective. Electrical current addition to ASR testing samples showed failure results achieved in less than one-half to one-third the time ASTM C 1293 standard prism beam testing needs to gain expansions of 0.04% or greater.

Figure 4-32: Expansion versus time for electrical cylinders (ASTM C 1293 modification)
(natural blue rock with high and low alkali cement)

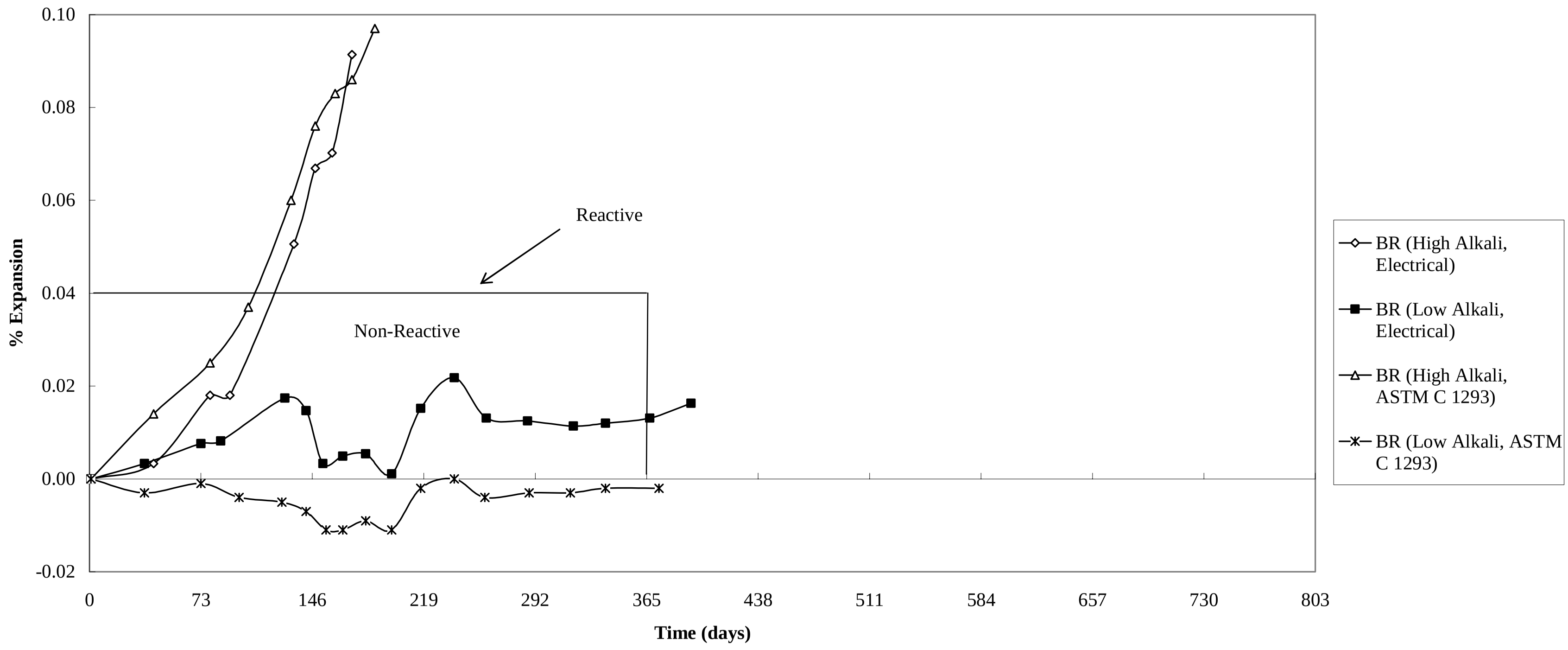


Figure 4-33: Expansion versus time for electrical cylinders (ASTM C 1293 modification) (RCA with high and low alkali cement)

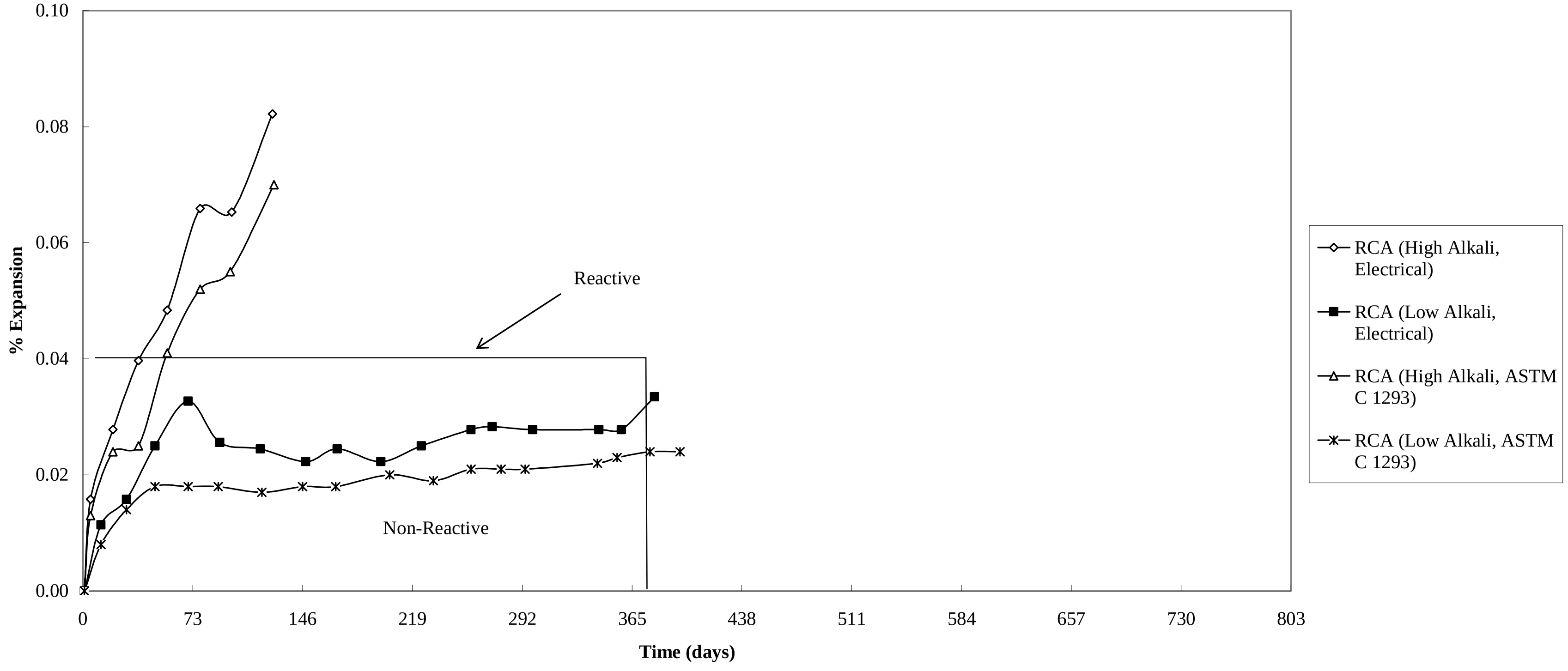


Figure 4-34: Expansion versus time for electrical cyclinders (ASTM C 1293 modification) (natural blue rock with class F fly ash)

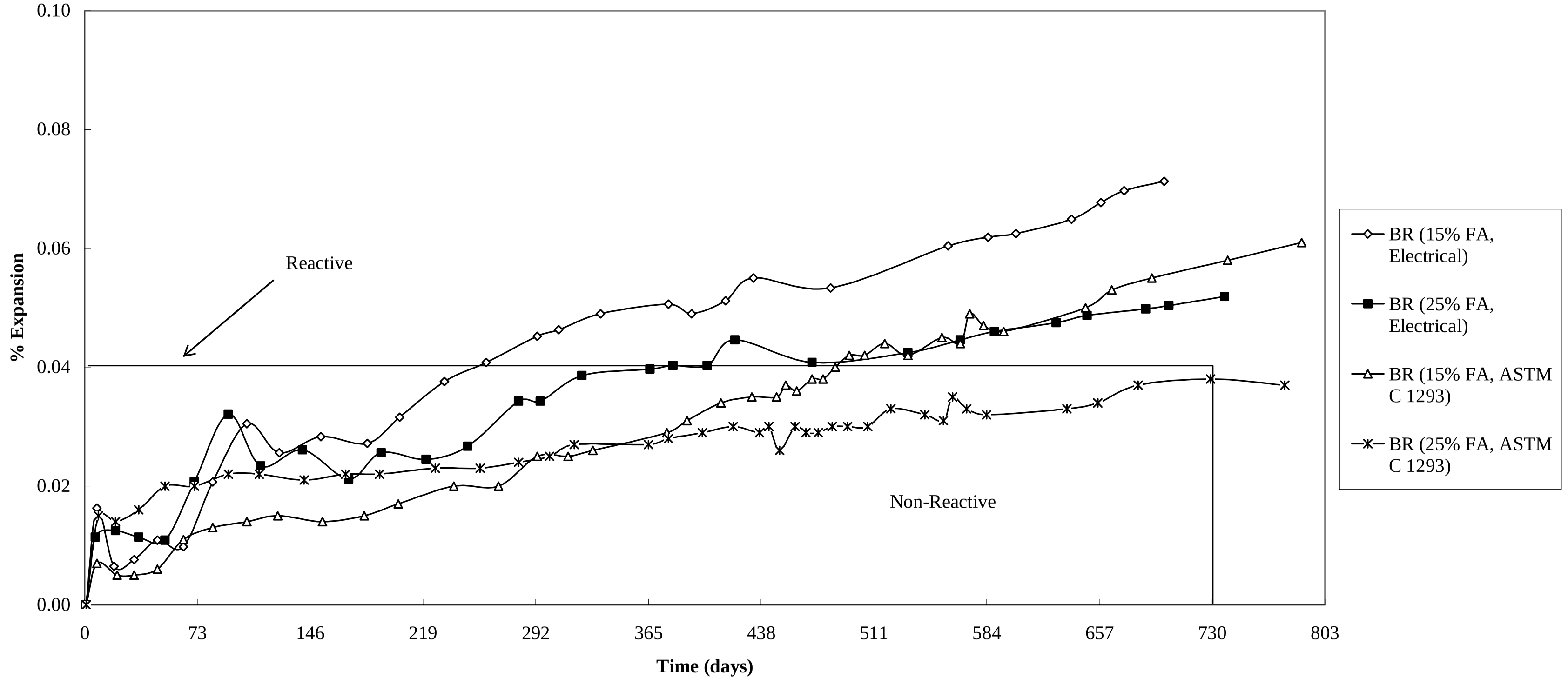


Figure 4-35: Expansion versus time for electrical cylinders (ASTM C 1293 modification) (RCA with class F fly ash)

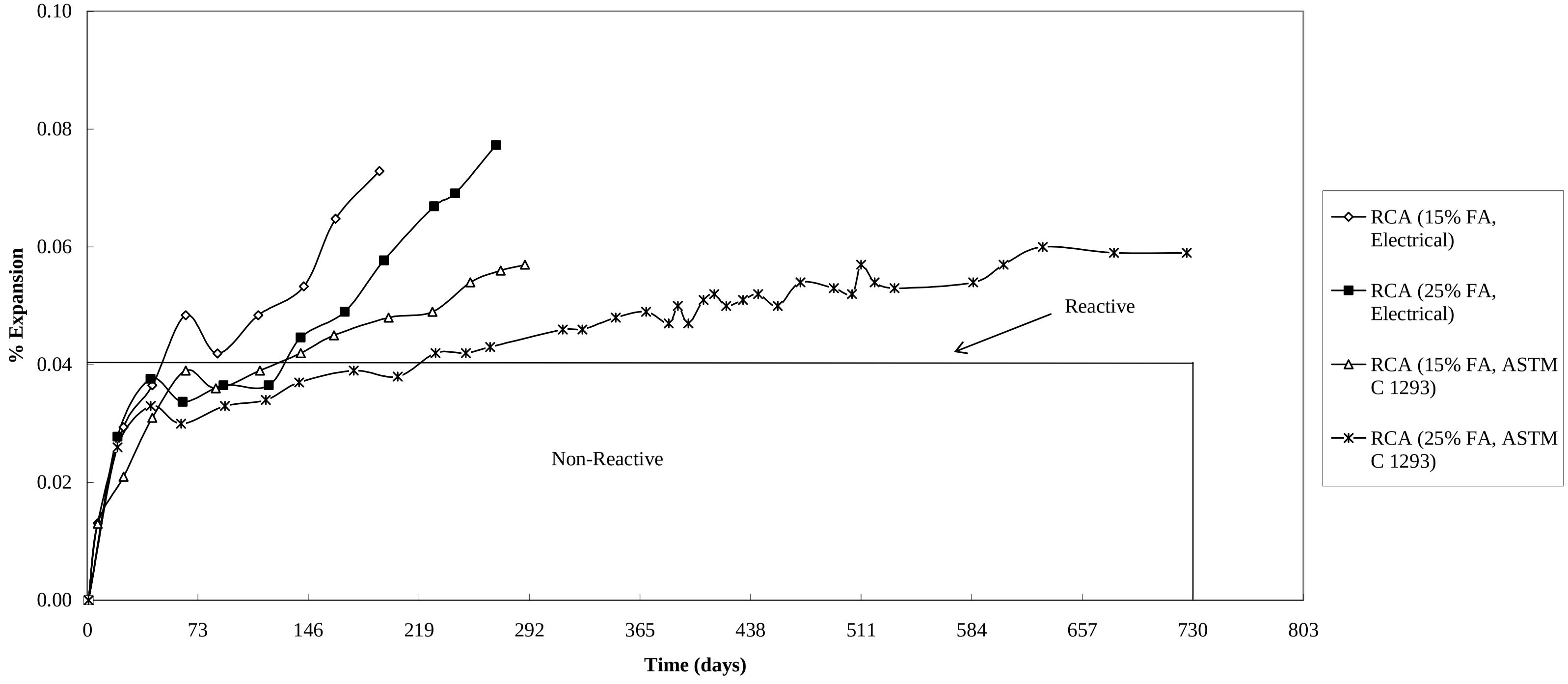


Figure 4-36: Expansion versus time for electrical cylinders (ASTM C 1293 modification) (natural blue rock with GGBFS)

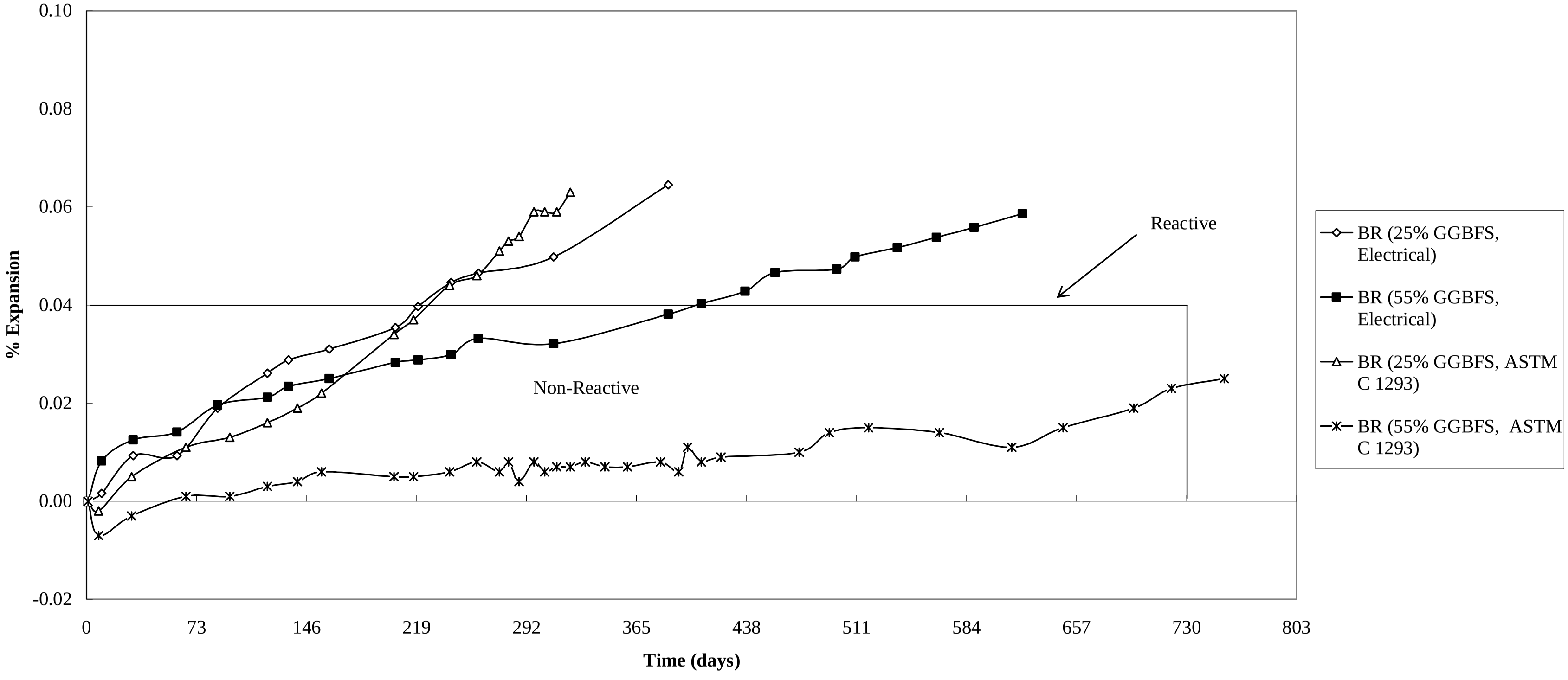


Figure 4-37: Expansion versus time for electrical cylinders (ASTM C 1293 modification) (RCA with GGBFS)

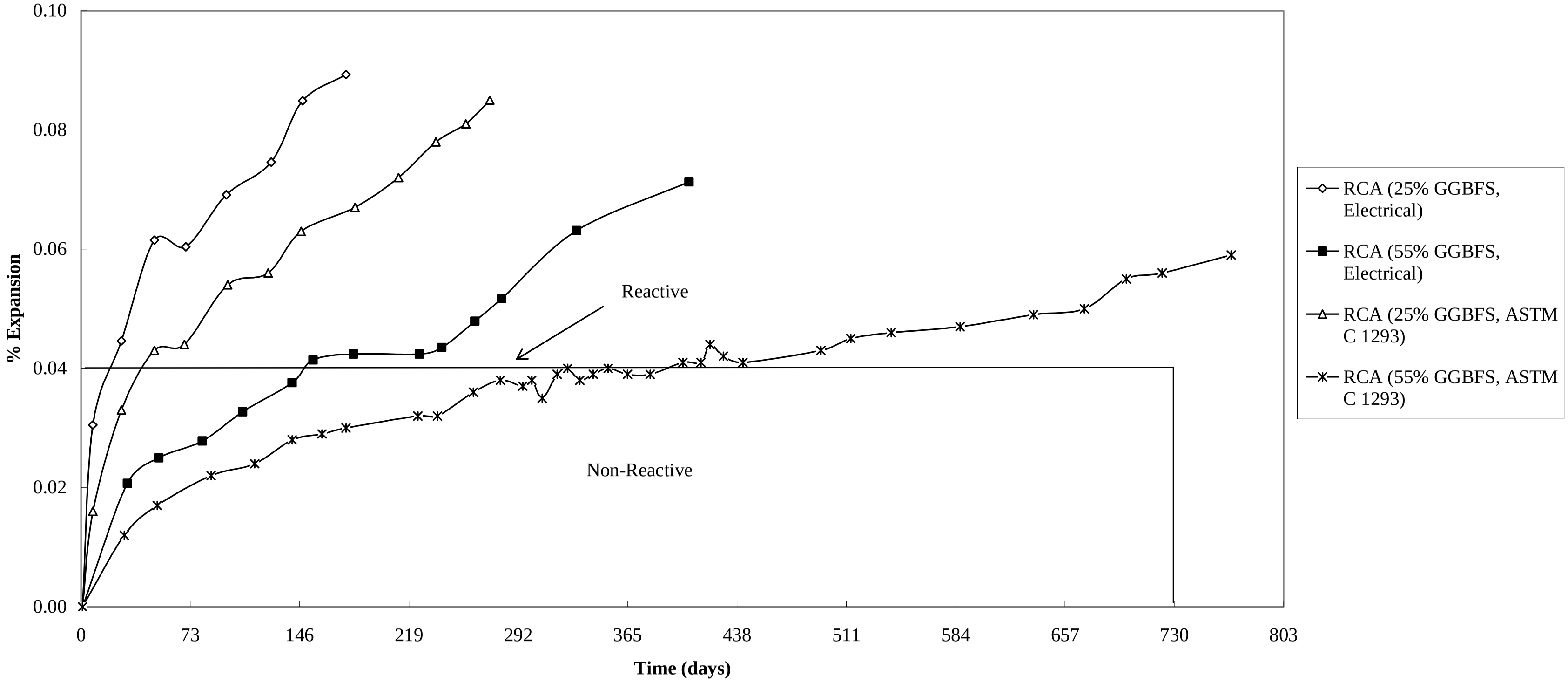


Figure 4-38: Expansion versus time for electrical cylinders (ASTM C 1293 modification) (natural blue rock with lithium nitrate)

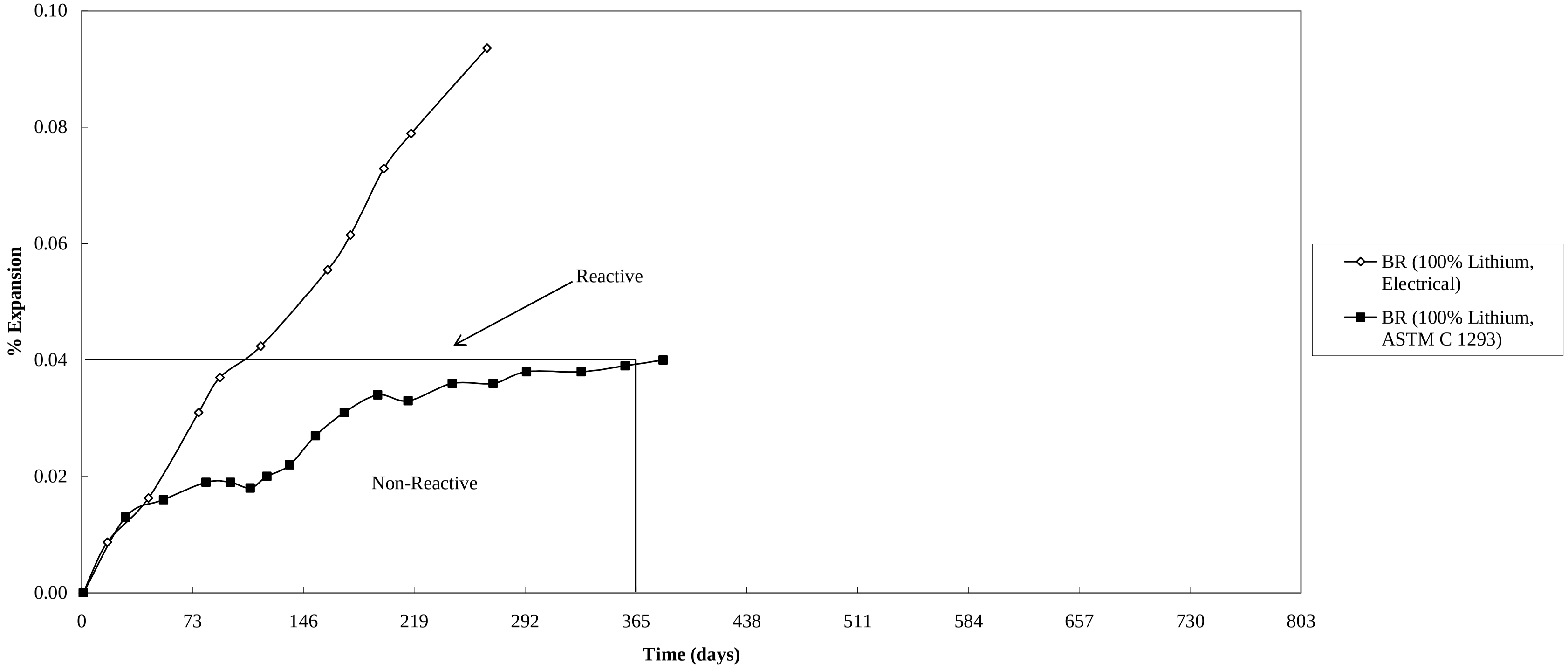


Figure 4-39: Expansion versus time for electrical cylinders (ASTM C 1293 modification) (RCA with lithium nitrate)

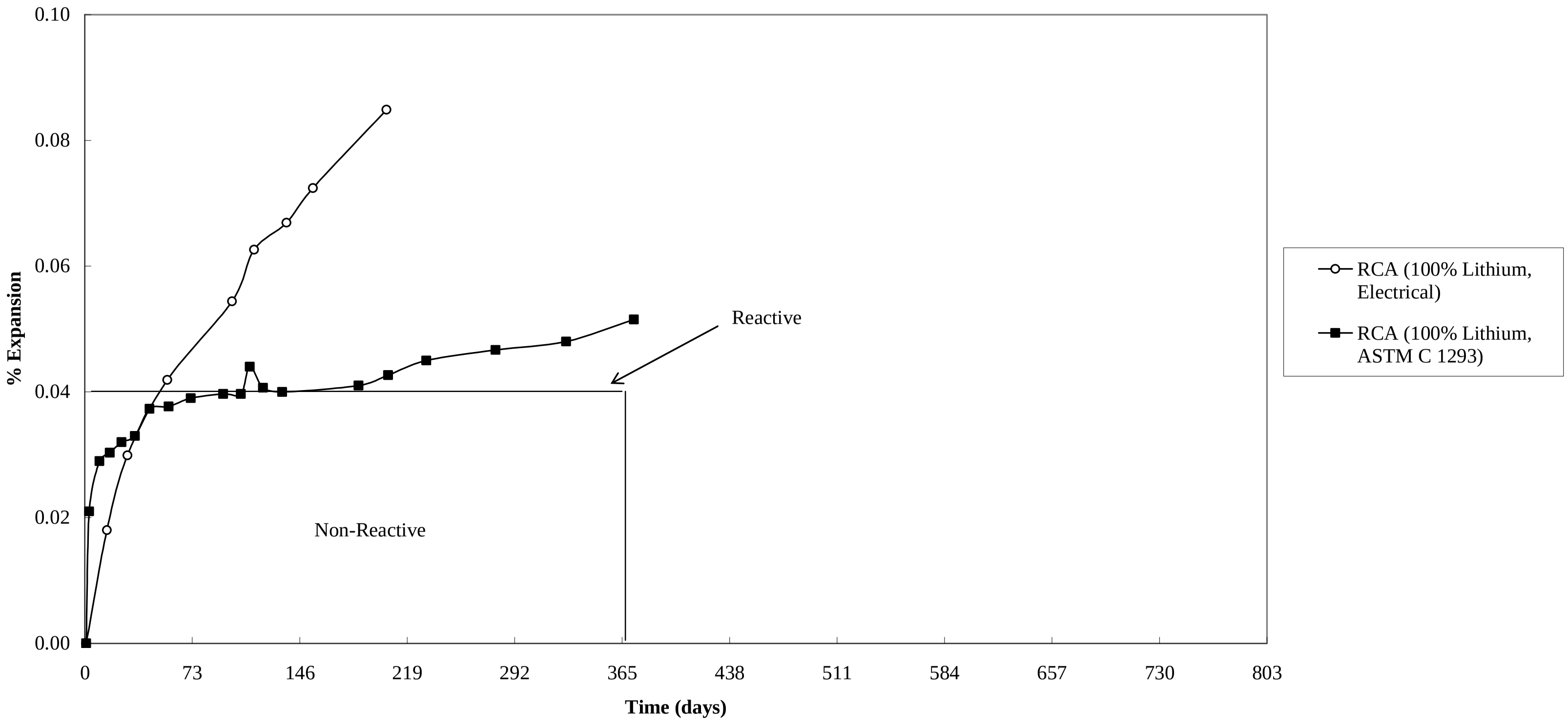


Figure 4-40: Expansion versus time for electrical cylinders (ASTM C 1293 modification) (natural blue rock with silica fume)

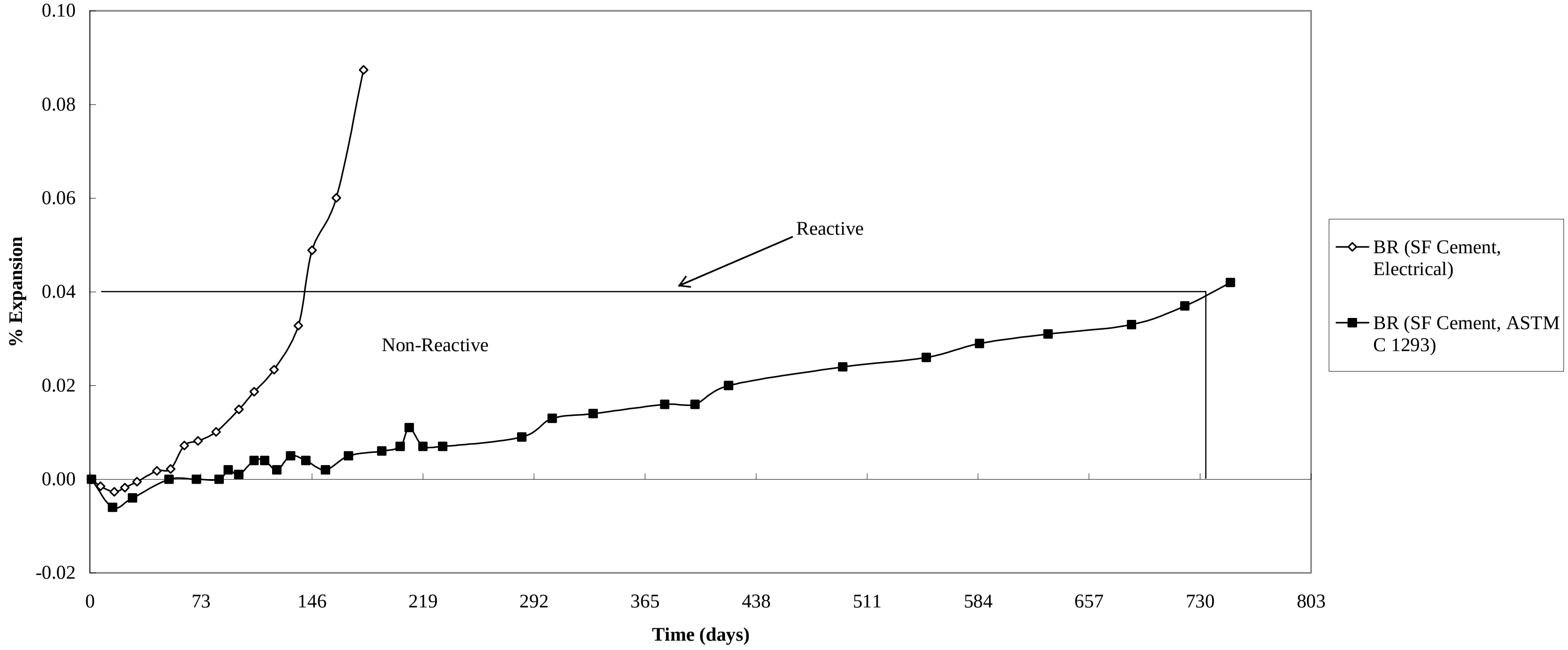
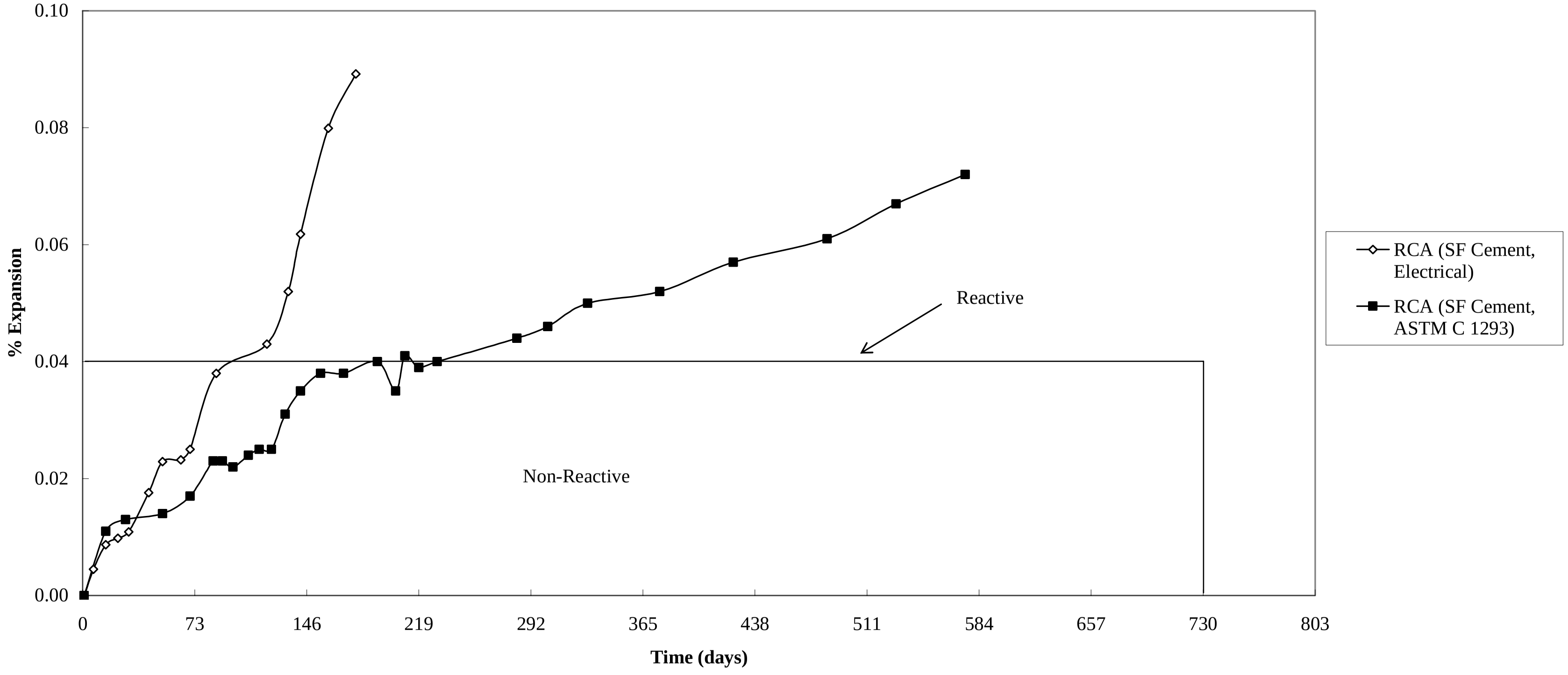


Figure 4-41: Expansion versus time for electrical cyclinders (ASTM C 1293 modification) (RCA with silica fume)



Cubes in NaOH Solution (Modified ASTM C 1260)

Modified ASTM C 1260 cubes with holes testing was a step forward from the ASTM C 1293 modified prism beam test where the sample was placed in an ASTM C 1260 mortar-bar environment. Like the vacuum-sealed cube test, this test was run to get potential ASR distress information about a concrete mixture in a faster time period than that of twenty-eight days with the modified prism beam test. The vacuum-sealed cube test shortened the standard prism beam test duration to sixty days from three hundred sixty five days to reach expansions of 0.04%. The modified cube test would be another way to incorporate recycled aggregate into a rapid testing environment, with no aggregate preparation needed before testing procedure was initialized. Modified ASTM C 1260 cube results are compared to modified ASTM C 1293 prism beam testing to find if expansion limits could be met in a faster manner by changing sample size and geometry.

All concrete testing mixtures were studied with this test incorporating natural blue rock and recycled blue rock aggregate. Mixtures included all cement and mitigation strategies so comparisons could easily be made with results from the modified prism beam data as presented in Figures 4-42 through 4-48.

Figures 4-42 shows expansion results for natural and recycled blue rock aggregate mixtures with high and low alkali cements. It was shown in both cases that modified cube samples expanded at a faster rate than modified beam samples. This observation was seen in past studies, but no accepted expansion feilure specification has been written for ASR testing with smaller cube samples as opposed to prism beams.[25]

Figures 4-43 shows expansion results for natural blue rock aggregate mixtures with low and high class F fly ash mitigations. It was shown in both cases that modified cube samples expanded at a faster rate than modified beam samples. Cube samples show failure expansions of 0.04% at half the time of modified prism beam samples.

Figures 4-44 shows expansion results for recycled blue rock aggregate mixtures with low and high class F fly ash mitigations. It was shown in both cases that modified cube samples expanded at a faster rate than modified beam samples. Cube samples show failure expansions of 0.04% at half the time of modified prism beam samples.

Both aggregate mixtures showed comparable data to previous modified cube testing with higher expansion characteristics, than with modified prism beam samples.

Figures 4-45 shows expansion results for natural blue rock aggregate mixtures with low and high GGBFS mitigations. It was shown in both cases that modified cube samples expanded at a faster rate than modified beam samples. Cube samples show failure expansions of 0.04% at greater than half the time of modified prism beam samples.

Figures 4-46 shows expansion results for recycled blue rock aggregate mixtures with low and high GGBFS mitigations. It was shown in both cases that modified cube samples expanded at a faster rate than modified beam samples. Cube samples show failure expansions of 0.04% at half the time of modified prism beam samples.

Both aggregate mixtures showed comparable data to previous modified cube testing with higher expansion characteristics, than with modified prism beam samples.

Figures 4-47 shows expansion results for natural and recycled blue rock aggregate mixtures with 100% lithium nitrate mitigation. It was shown in both cases that modified cube samples expanded at a faster rate than modified beam samples. Cube samples show failure expansions of 0.04% at over half the time of modified prism beam samples.

Both aggregate mixtures showed comparable data to previous modified cube testing with higher expansion characteristics, than with modified prism beam samples.

Figures 4-48 shows expansion results for natural and recycled blue rock aggregate mixtures with 8% silica fume mitigation. It was shown in both cases that modified cube samples expanded at a faster rate than modified beam samples. Cube samples show failure expansions of 0.04% at approximately half the time of modified prism beam samples.

Both aggregate mixtures showed comparable data to previous modified cube testing with higher expansion characteristics, than with modified prism beam samples.

Higher expansion levels with modified cube samples showed the modified prism beam testing procedures could be further adjusted by changing sample size and geometry to shorten testing duration.

Figure 4-42: Expansion versus time for cubes in NaOH solution (ASTM C 1260 modification)
(natural blue rock and RCA with high alkali cement)

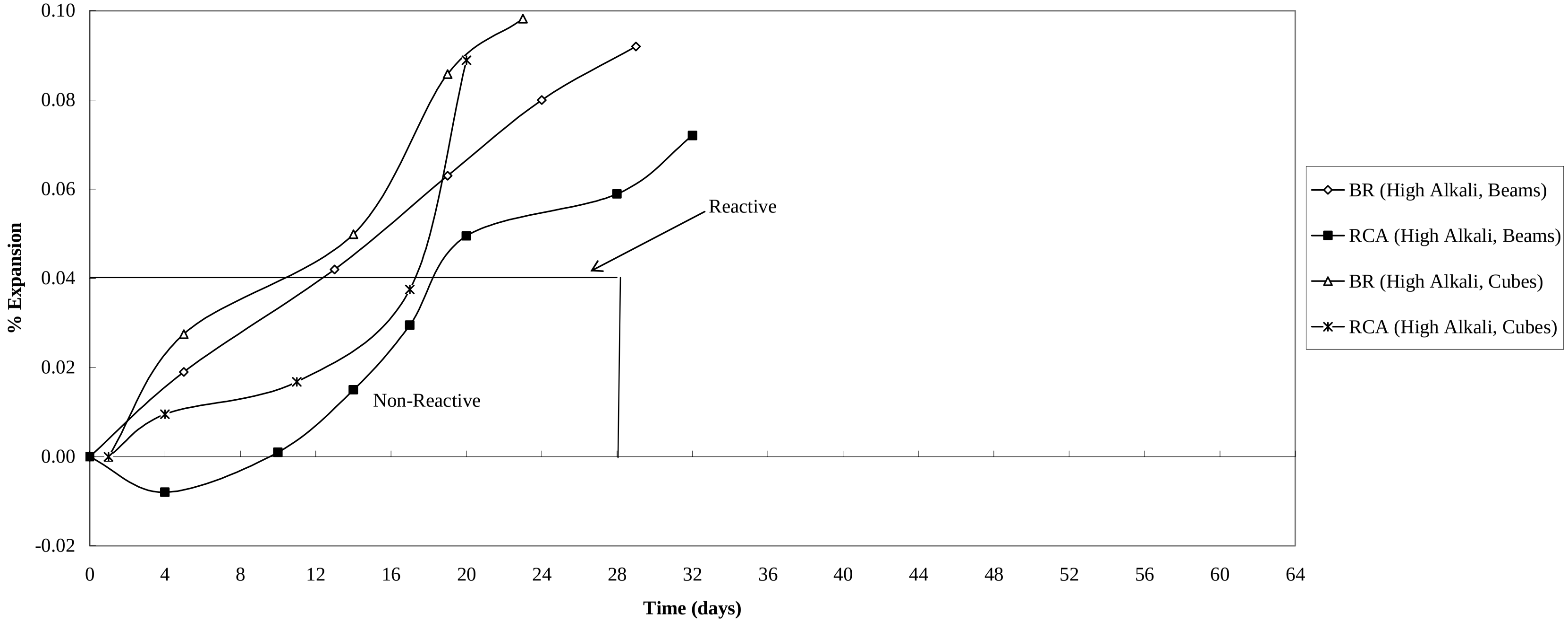


Figure 4-43: Expansion versus time for cubes in NaOH solution (ASTM C 1260 modification) (natural blue rock with class F fly ash)

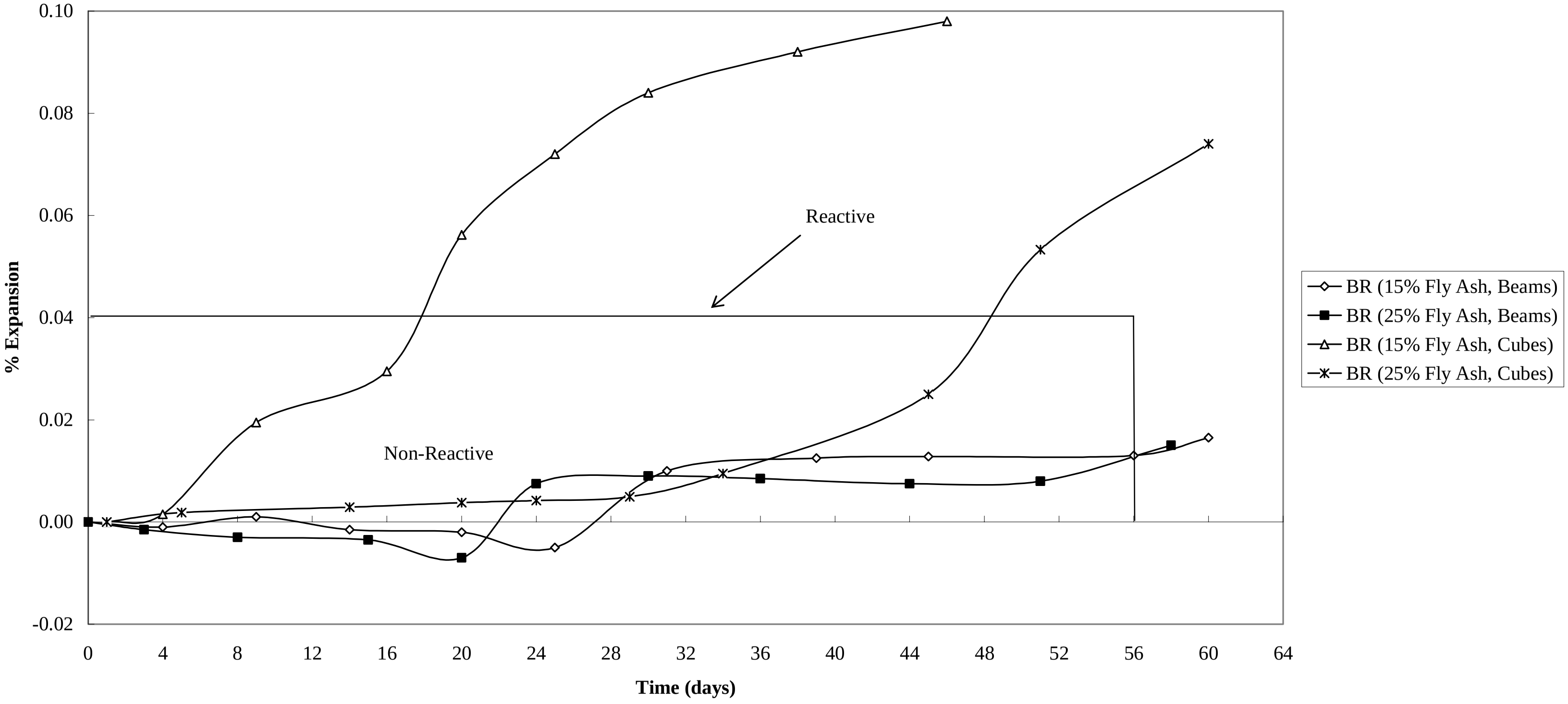


Figure 4-44: Expansion versus time for cubes in NaOH solution (ASTM C 1260 modification)
(RCA with class F fly ash)

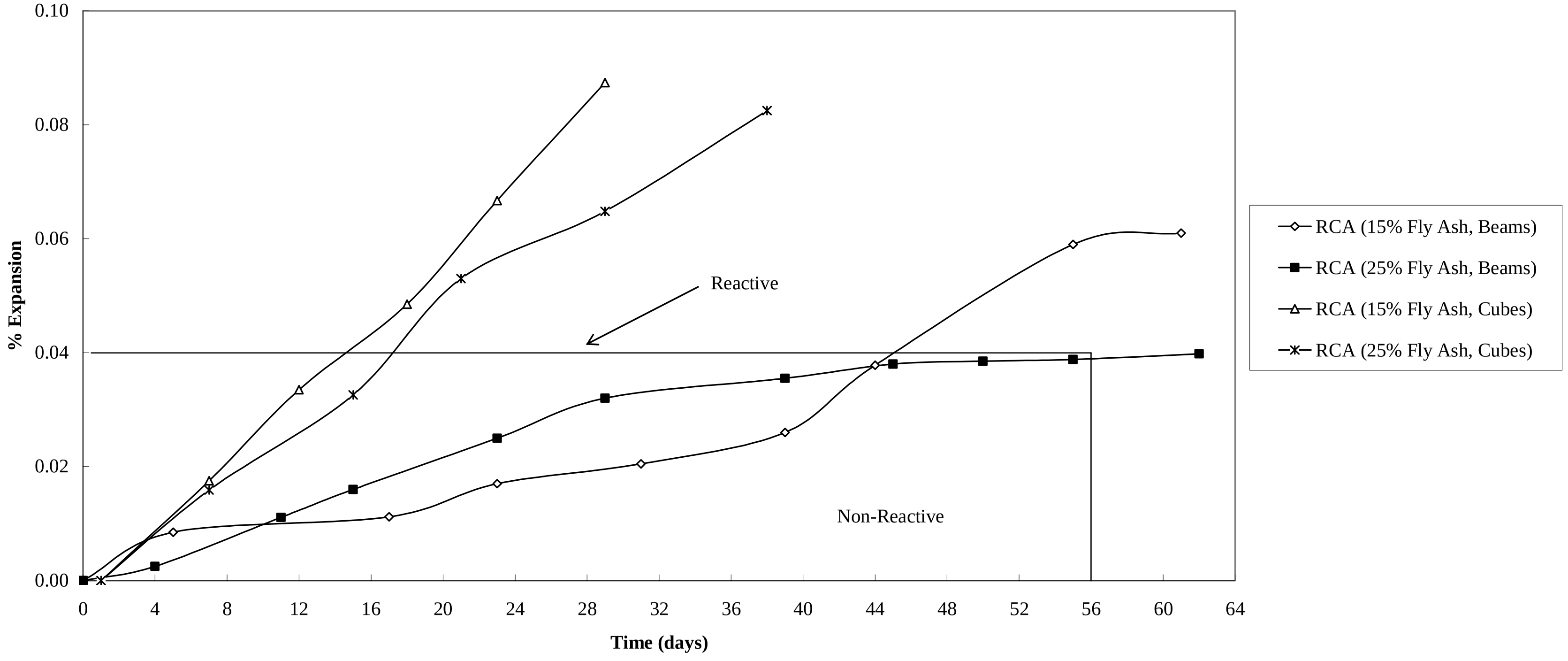


Figure 4-45: Expansion versus time for cubes in NaOH solution (ASTM C 1260 modification)
(natural blue rock with GGBFS)

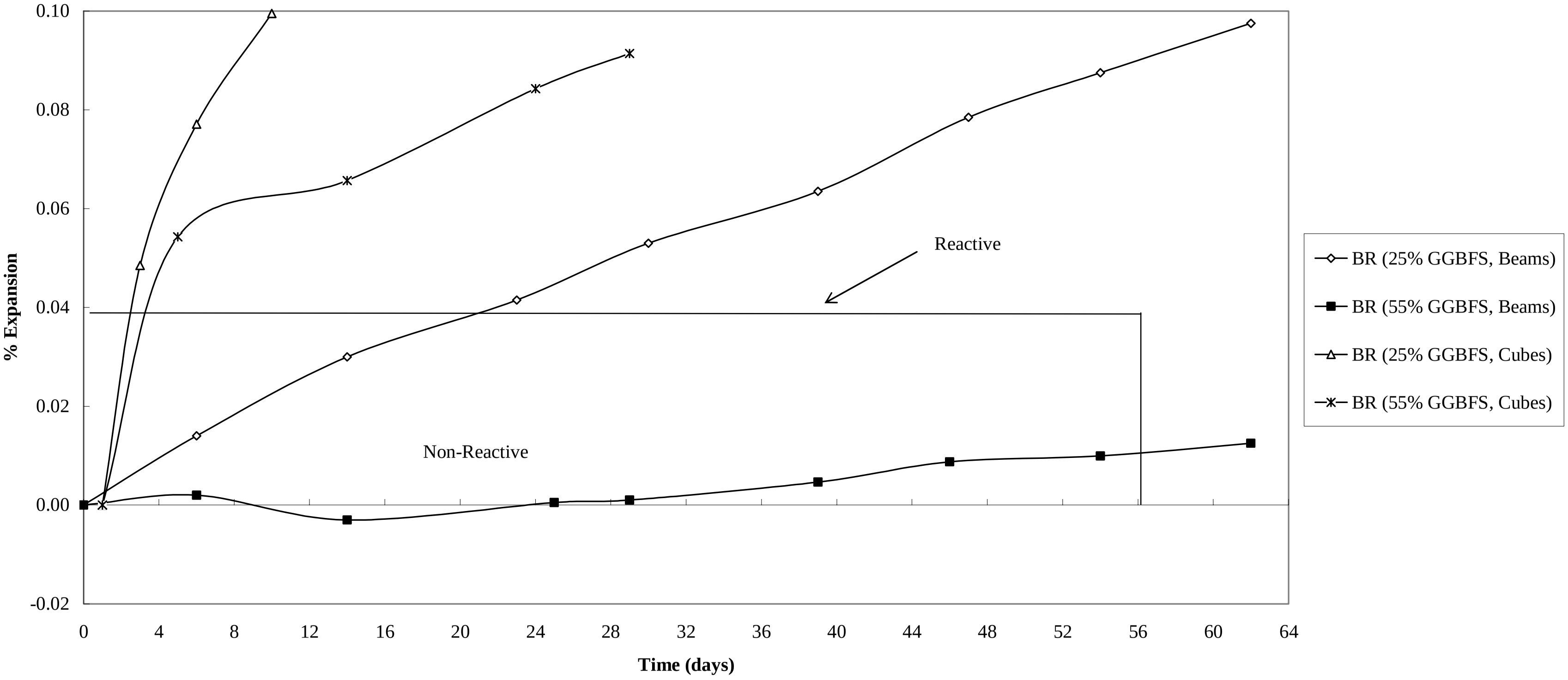


Figure 4-46: Expansion versus time for cubes in NaOH solution (ASTM C 1260 modification)
(RCA with GGBFS)

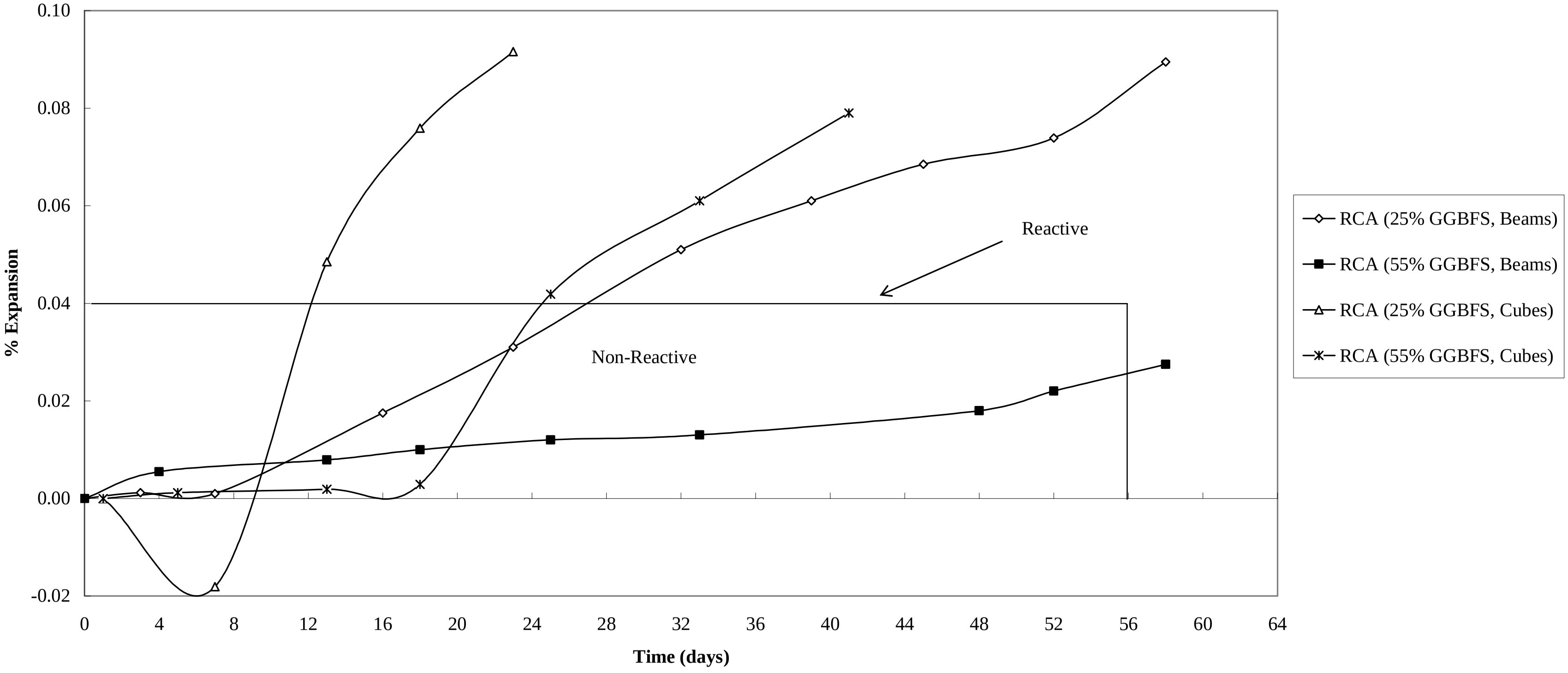


Figure 4-47: Expansion versus time for cubes in NaOH solution (ASTM C 1260 modification) (natural blue rock with lithium nitrate)

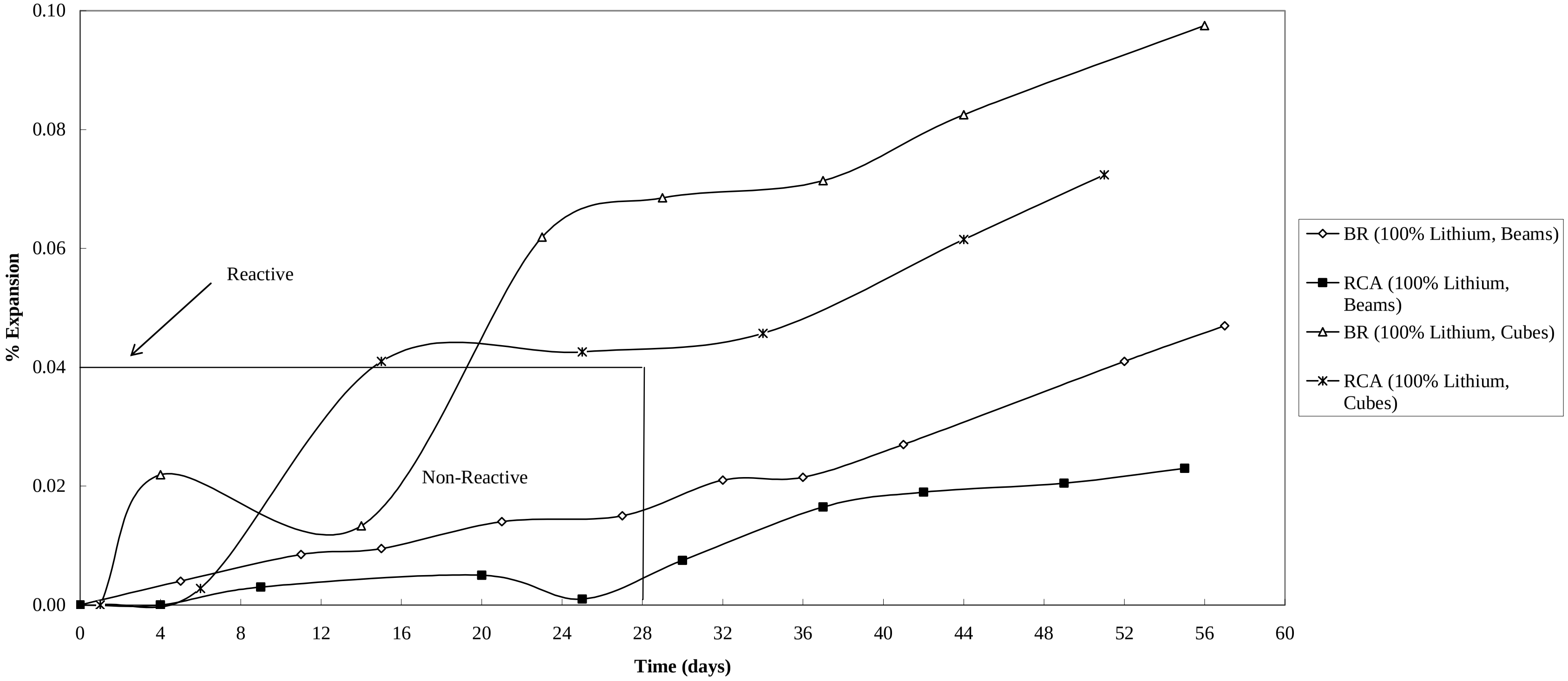
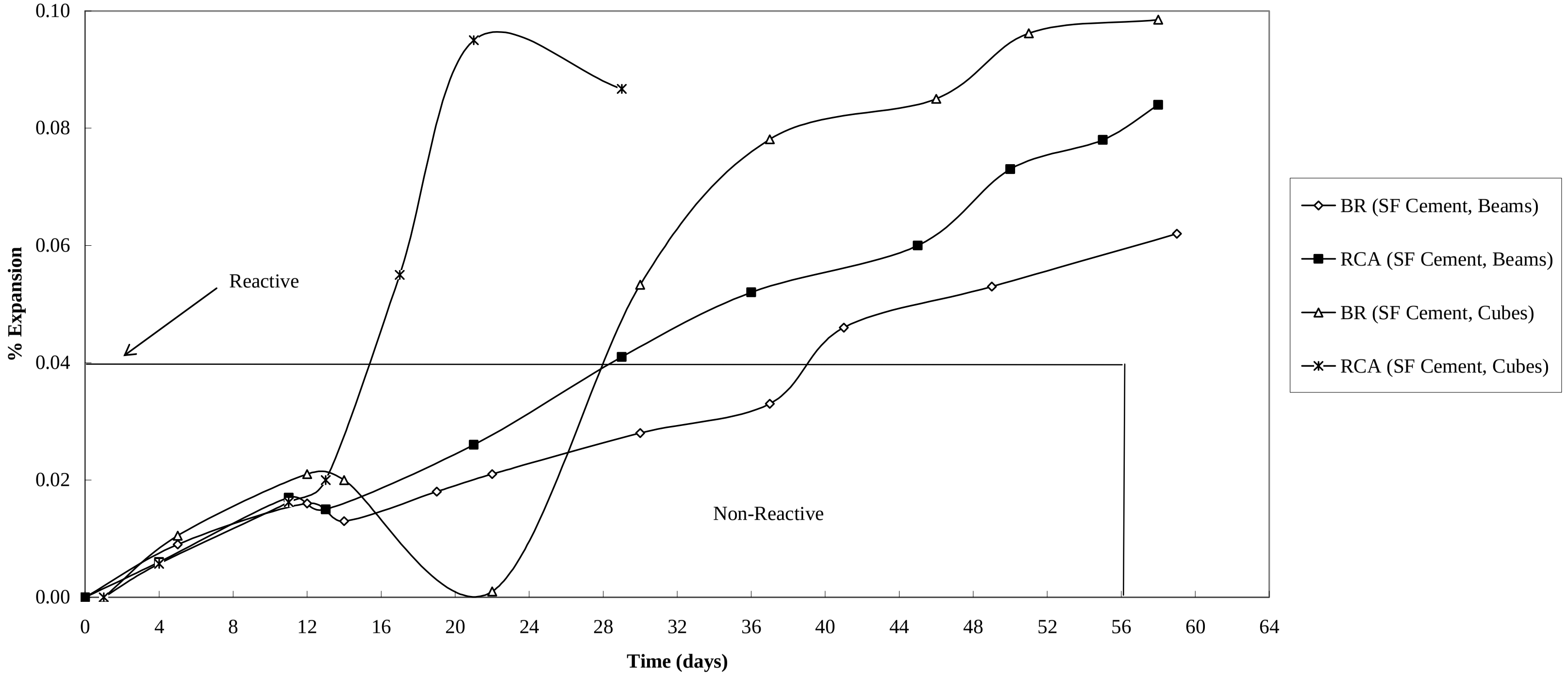


Figure 4-48: Expansion versus time for cubes in NaOH solution (ASTM C 1260 modification) (natural blue rock and RCA with silica fume)



SUMMARY OF RESULTS

Rapid Testing Procedures

ASTM C 1260 (Mortar-Bar Method)

This testing procedure gave accurate screening results for aggregates with ASR potential characterization. Limestone aggregate was characterized as non-reactive and natural and recycled blue rock aggregates were characterized as potentially reactive. The mitigation strategies were properly characterized as to their abilities to control ASR distress with the natural blue rock aggregate as well as the recycled aggregate testing. Used with ASTM C 1293 standard prism beam testing, an aggregate and concrete mixture can be properly tested and characterized to its potential ASR behavior.[20,59]

ASTM C 1293 (Modified Prism Beam Test)

A recycled aggregate rapid screening test is not available in ASTM specifications that matched the capabilities of ASTM C 1260 mortar-bar testing. The ASTM C 1293 modified prism beam test showed comparable results with limestone and natural blue rock aggregate mixtures when compared to ASTM C 1260 mortar-bar test data. Recycled aggregate mixtures could be tested with the modified procedure with no aggregate machining necessary. Modified ASTM C 1293 prism beam testing showed comparable results to published ASTM ASR testing procedures.

Figure 4-49 shows the correlation between the Modified Prism Beam Test at 28 days and the Mortar-Bar Method test at 14 days. This shows an excellent correlation between the two tests by agreeing when the samples pass as well as fail the expansion criteria. Figures 4-50 shows a similar relationship between the two tests, but at 56 and 28 days, respectively. The criteria of increased testing periods (56 days versus 28 days for the prisms and 28 days versus 14 days for the mortar-bars) are required when mitigation is utilized. If the testing durations are not increased some mitigation procedures may be conservative and ultimately lead to premature failure in the field.

Standard Testing Procedures

ASTM C 1293 (Standard Prism Beam)

The standard prism beam test has the best reputation in producing accurate ASR characterization with PCC mixtures. It was used with ASTM C 1260 mortar-bar testing to properly characterize all PCC mixtures studied to their potential ASR reactivity. With these results, modified testing comparison could be done to observe whether modified results were comparative and accurate to properly characterize ASR potential with aggregate and PCC mixtures.

ASTM C 1293 (Standard Prism Beam) w/ saturation

Adjustments made to recycled aggregate showed beneficial results with initial expansion behavior lessened. Recycled aggregate, showing much larger absorptive characteristics when compared to natural aggregates, was saturated to eliminate moisture expansion and only show ASR expansion. The procedures were successful and data was comparable to non-saturated natural blue rock aggregate concrete data.

Figure 4-51 shows the correlation between the ASTM C 1293 one-year prisms and the ASTM C 1260 28-day prism test. Figure 4-52 shows the correlation between the ASTM C 1293 two-year prisms and the ASTM C 1260 56-day prism test. The correlation between the two tests is very encouraging for the various forms of mitigation strategies evaluated. The two test procedures give consistent results in either accepting or failing a given mitigated concrete mixture. This not only suggests a lower cost of testing, but also gives confidence in determining the equivalence of testing for two years in only one month.

Modified Testing Procedures

ASTM C 1293 (Vacuum-Sealed Cubes)

Vacuum-sealed cube testing showed comparable results to ASTM C 1293 standard prism beam testing in one-sixth the time. Results were also comparable to ASTM C 1260 mortar-bar and ASTM C 1293 modified prism beam testing data. The failure criteria of 0.04% expansion at fifty days were comparable to 0.04% expansion at one year, for ASTM C 1293 standard prism beam testing. An accelerated testing procedure is necessary to quicken laboratory testing time with PCC construction projects that have strict budget and building time schedules.

ASTM C 1293 (Electrical Cylinders)

Another attempt to accelerate ASTM C 1293 standard prism beam testing was the introduction of electric current into the concrete. ASR can be induced with cathodic protection procedures. Expansion rates were increased with electrical current testing compared to those seen with ASTM C 1293 prism beam testing.

ASTM C 1260 (Modified Cubes in NaOH Solution)

Results showed increased expansion rates with ASTM C 1260 modified cube testing when compared to ASTM C 1293 modified prism beam testing. The modified cube test was done to accelerate the modified prism beam procedure and gain ASR potential results faster. This was accomplished with sample size and geometry changes and introducing the samples to one normal NaOH solution. The solution was able to penetrate the samples from the outside in and the inside out, utilizing cast holes into the cubes. Results show that expansion data could be gained faster with the cubes, when compared to prism beams.

Table 4-1 summarizes all test results for this study.

Table 4-1: Test Result Summary

Concrete Mixture	**Mixture Components**	**Testing Conditions**	**Pass**	**Fail**
1	A, D, J & K	1	X	
2	A, E, J & K	1	X	
3	B, D, J & K	1		X
4	B, E, J & K	1		X
11	C, D, J & K	1		X
5	B, D, G_a, J & K	1		X
6	B, D, G_b, J & K	1		X
7	B, D, H_a, J & K	1		X
8	B, D, H_b, J & K	1	X	
10	B, D, I, J & K	1	X	
9	B, F, J & K	1		X
1	A, D, J & K	2	X	
2	A, E, J & K	2	X	
3	B, D, J & K	2		X
11	C, D, J & K	2		X
5	B, D, G_a, J & K	2	X	
6	B, D, G_b, J & K	2	X	
13	C, D, G_a, J & K	2		X
14	C, D, G_b, J & K	2		X
7	B, D, H_a, J & K	2		X
8	B, D, H_b, J & K	2	X	
15	C, D, H_a, J & K	2		X
16	C, D, H_b, J & K	2	X	
10	B, D, I, J & K	2	X	
18	C, D, I, J & K	2	X	
9	B, F, J & K	2		X
17	C, F, J & K	2		X
3	B, D, J & K	4		X
4	B, E, J & K	4	X	
11	C, D, J & K	4		X
12	C, E, J & K	4	X	
5	B, D, G_a, J & K	4		X
6	B, D, G_b, J & K	4	X	
13	C, D, G_a, J & K	4		X
14	C, D, G_b, J & K	4		X
7	B, D, H_a, J & K	4		X

Table 4-1: Test Result Summary (Cont.)

Concrete Mixture	Mixture Components	Testing Conditions	Pass	Fail
8	B, D, H_b, J & K	4	X	
15	C, D, H_a, J & K	4		X
16	C, D, H_b, J & K	4		X
10	B, D, I, J & K	4	X	
18	C, D, I, J & K	4		X
9	B, F, J & K	4	X	
17	C, F, J & K	4		X
1	A, D, J & K	4	X	
2	A, E, J & K	4	X	
11	C, D, J & K	4 (Saturation)		X
11	C, D, J & K	4 (Vacuum Saturation)		X
14	C, D, G_b, J & K	4 (Saturation)	X	
14	C, D, G_b, J & K	4 (Vacuum Saturation)	X	
16	C, D, H_b, J & K	4 (Saturation)		X
16	C, D, H_b, J & K	4 (Vacuum Saturation)		X
18	C, D, I, J & K	4 (Saturation)	X	
18	C, D, I, J & K	4 (Vacuum Saturation)	X	
17	C, F, J & K	4 (Saturation)		X
17	C, F, J & K	4 (Vacuum Saturation)		X
3	B, D, J & K	5	X	
4	B, E, J & K	5	X	
11	C, D, J & K	5	X	
12	C, E, J & K	5	X	
5	B, D, G_a, J & K	5		X
6	B, D, G_b, J & K	5		X
13	C, D, G_a, J & K	5		X
14	C, D, G_b, J & K	5		X
14	C, D, G_b, J & K	5 (Saturation)		X
7	B, D, H_a, J & K	5		X
8	B, D, H_b, J & K	5		X
15	C, D, H_a, J & K	5		X
16	C, D, H_b, J & K	5		X
16	C, D, H_b, J & K	5 (Saturation)		X
10	B, D, I, J & K	5	X	
18	C, D, I, J & K	5	X	
9	B, F, J & K	5	X	
17	C, F, J & K	5		X
17	C, F, J & K	5 (Saturation)	X	
3	B, D, J & K	6		X
4	B, E, J & K	6	X	
11	C, D, J & K	6		X
12	C, E, J & K	6	X	

Table 4-1: Test Result Summary (Cont.)

Concrete Mixture	**Mixture Components**	**Testing Conditions**	**Pass**	**Fail**
5	B, D, G_a, J & K	6		X
6	B, D, G_b, J & K	6	X	
13	C, D, G_a, J & K	6		X
14	C, D, G_b, J & K	6		X
7	B, D, H_a, J & K	6		X
8	B, D, H_b, J & K	6	X	
15	C, D, H_a, J & K	6		X
16	C, D, H_b, J & K	6		X
10	B, D, I, J & K	6	X	
18	C, D, I, J & K	6	X	
9	B, F, J & K	6	X	
17	C, F, J & K	6		X
3	B, D, J & K	3		X
11	C, D, J & K	3		X
5	B, D, G_a, J & K	3		X
6	B, D, G_b, J & K	3		X
13	C, D, G_a, J & K	3		X
14	C, D, G_b, J & K	3		X
7	B, D, H_a, J & K	3		X
8	B, D, H_b, J & K	3		X
15	C, D, H_a, J & K	3		X
16	C, D, H_b, J & K	3		X
10	B, D, I, J & K	3		X
18	C, D, I, J & K	3		X
9	B, F, J & K	3		X
17	C, F, J & K	3		X

(Note: Test result data appears in this table as it is written previously in the section, by testing condition)

Legend: (See next page)

Material Overview:

Aggregates (Coarse):	Cement:
A – South Wallingford Limestone	D – High Alkali Dragon Cement
B – Westbrook Blue Rock	
C – RCA Westbrook Blue Rock	

Table 4-1: Test Result Summary (Cont.)

Mitigation Strategies:

E – Low Alkali Cement
F – Silica Fume Blended Cement
G – Class F Fly Ash
H – GGBFS
I – Lithium Nitrate ($LiNO_3$)

Admixture:

J – Air Entrainment (Darex II)

Aggregate (Fine):

K – Ossipee Glacial Sand

(Note: a - represents low mitigation & b - represents high mitigations for G & H)

Testing Overview:

ASTM C 1260 Testing:

1 – Mortar-Bar Method
2 – Modified Prism Beam
3 – Modified Cube

ASTM C 1293 Testing:

4 – Standard Prism Beam
5 – Modified Cube (Vacuum Sealed)
6 – Modified Electrical Cylinders

Figure 4-49: Modified ASTM C 1260 28-Day Prism Beam versus ASTM C 1260 14-Day Mortar Bar Results

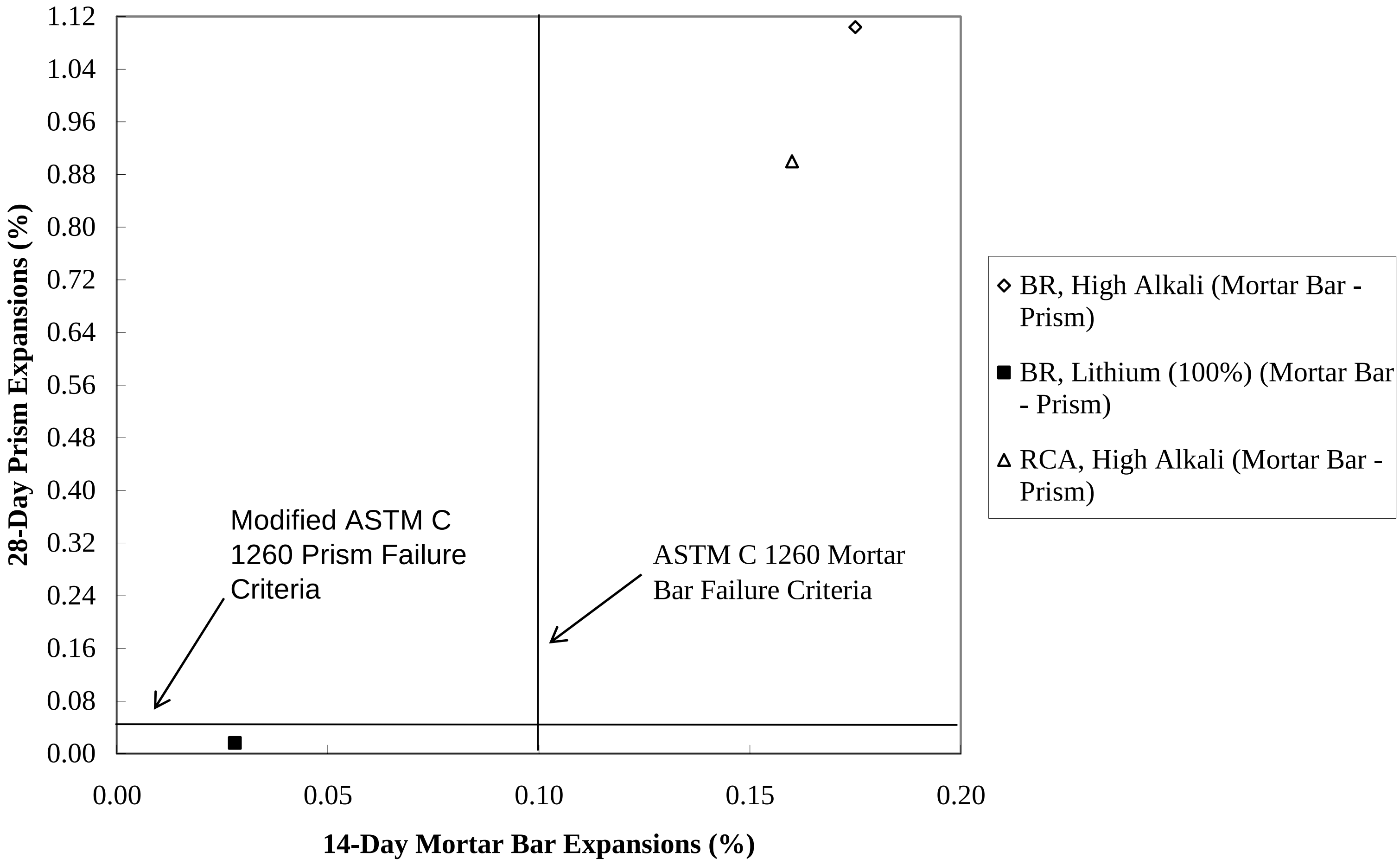


Figure 4-50: Modified ASTM C 1260 56-Day Prism versus ASTM C 1260 28-Day Mortar Bar Results

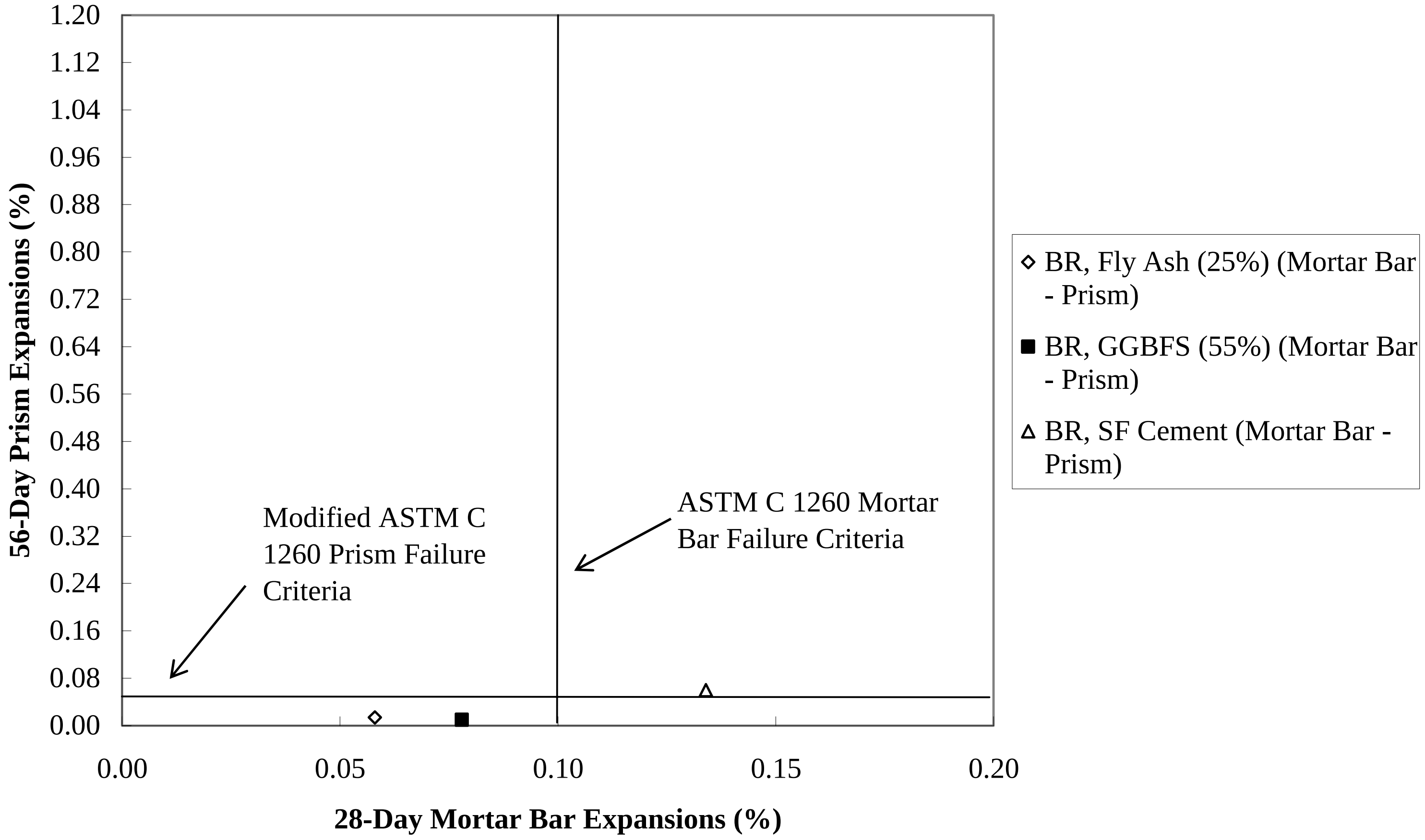


Figure 4-51: ASTM C 1293 365-Day Prism versus Modified ASTM C 1260 28-Day Prism Results

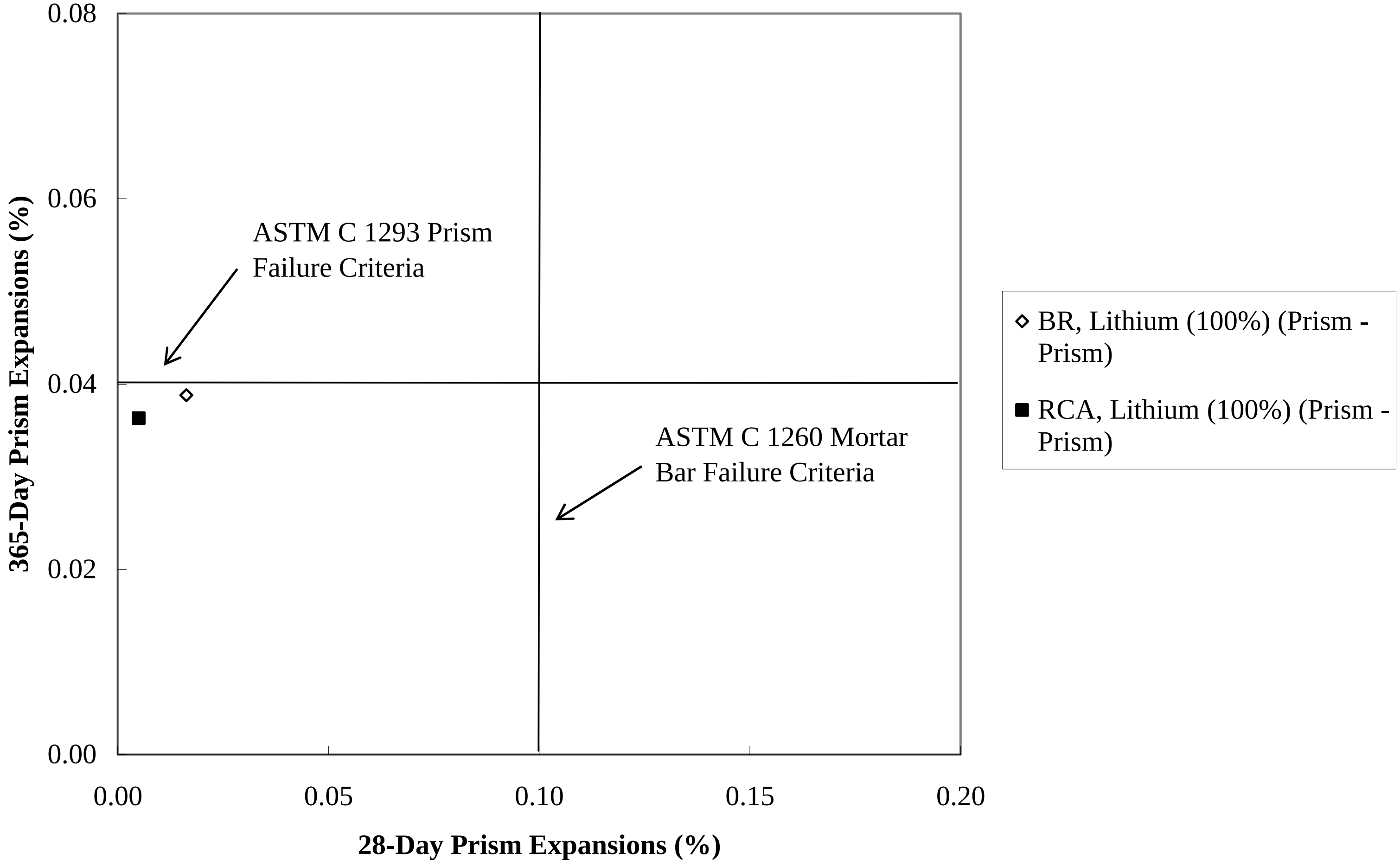
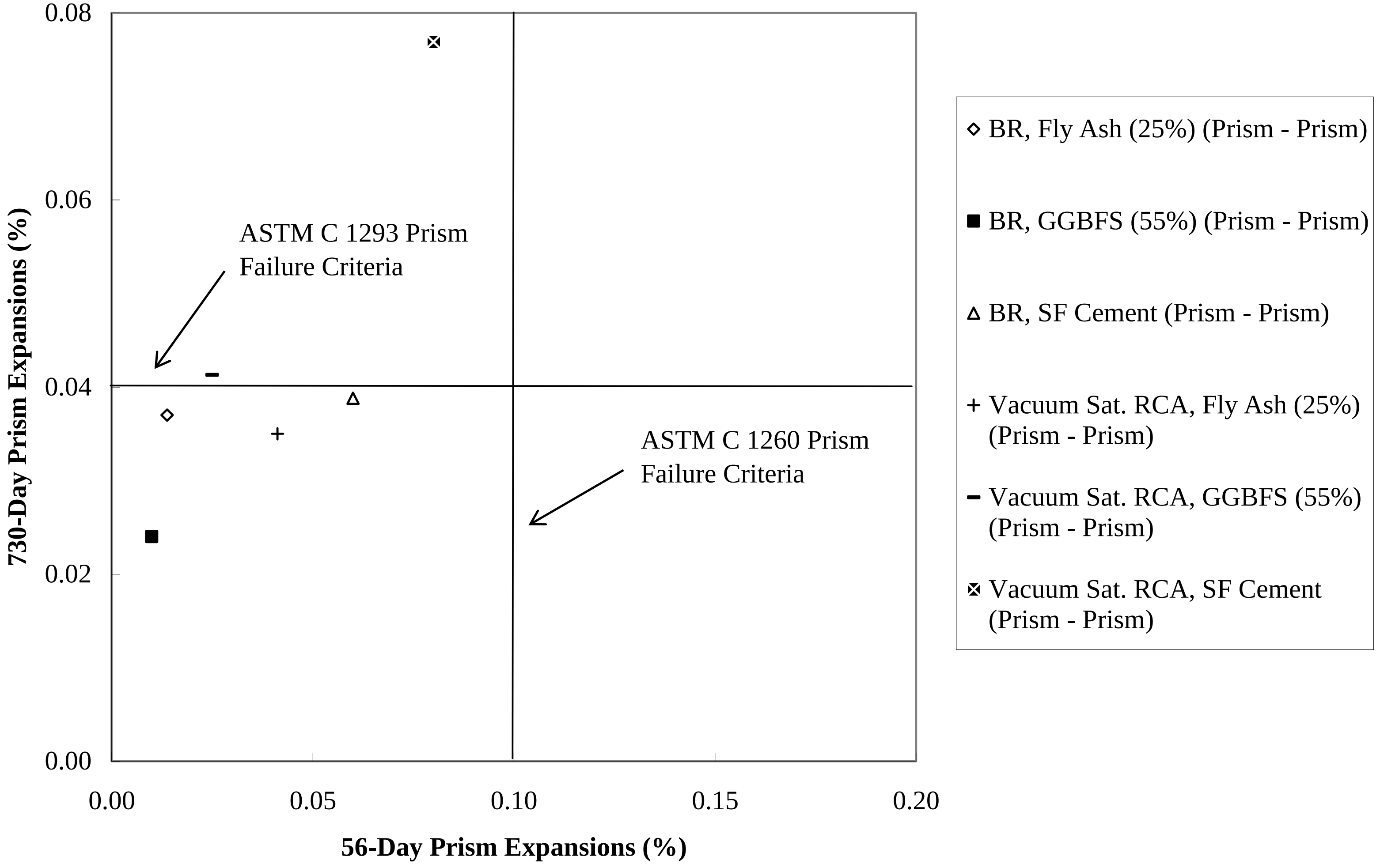


Figure 4-52: ASTM C 1293 720-Day versus Modified ASTM C 1260 56-Day Prism Results



CHAPTER 5

CONCLUSIONS

INTRODUCTION

Proven ASR mitigation strategies used with natural aggregate concretes were reviewed with recycled aggregate concrete. Low alkali cement, class F fly ash, GGBFS, lithium nitrate, and silica fume blended cement were tested to study their ability to control deleterious ASR expansion behavior. Although ASR has been studied in detail with past research projects, little is known about concrete incorporating recycled concrete aggregate and ASR potential. Recycled aggregates are used more commonly in present day construction practices and their potential to suffer ASR distress when put back into fresh concrete mixtures is an important aspect that needed to be studied in further detail.

An overview of results is discussed in this section. Mitigation strategies ability to control ASR distress with recycled aggregate concrete, having shown ASR distress before recycling, and the applicability of presently used ASR testing procedures with this material are discussed.

NATURAL BLUE ROCK AGGREGATE CONCRETE

Initial testing was done with natural blue rock aggregate concrete, similar aggregate used in the concrete that produced the recycled aggregate. Comparisons were made with both aggregates, natural and recycled, used in concrete mixtures to observe differences that may arise with ASR expansion data. Natural blue rock aggregate concrete was first reviewed and conclusions are as follows.

Natural Blue Rock Aggregate Concrete Conclusions

1. Low alkali cement, 25% class F fly ash cement substitution, 55% GGBFS cement substitution, 100% lithium nitrate dosage, and 8% silica fume substitution controlled ASR expansion below limits with a potentially reactive natural blue rock quartzite aggregate. The substitution mixtures were used in a concrete mixture that incorporated cement with 1.31% total alkali content.

2. ASTM C 1260 (mortar-bar) testing (except for low alkali cement), modified ASTM C 1293 prism beam testing, and ASTM C 1293 prism beam testing all showed comparable results that natural blue rock quartzite shows non-reactive ASR characteristics when used with appropriate mitigation strategies.

3. Both modified ASTM C 1293 prism beam and ASTM C 1260 cube sample testing showed accelerated expansion at a greater rate than for ASTM C 1293 prism beam tests.

4. Modified ASTM C 1293 prism beam failure criteria, 0.04% expansion at twenty-eight days, showed good correlation to ASTM C 1293 prism beam failure criteria, 0.04% expansion at one year.

5. Modified ASTM C 1293 vacuum-sealed cube failure criteria, 0.04% expansion at fifty days, showed good correlation to modified and standard ASTM C 1293 prism beam testing.

6. Electrical current testing showed an increased rate of expansion with comparable results when compared to ASTM C 1293 prism beam results with failure criteria of 0.04% at one year.

7. Modified ASTM C 1260 cube testing showed an increased rate of expansion when compared to modified ASTM C 1293 vacuum-sealed cube testing. Both cube testing

methods produced results with a higher variation between like data points than any other testing procedures incorporated in this research.

8. Standard ASR test applicability with the modified ASTM C 1293 prism beam testing procedure showed comparative results to standard test procedures.

9. Previously developed ASR mitigation guidelines control deleterious ASR expansion behavior with "potentially reactive" aggregate sources as defined by ASTM C 1260 (mortar-bar method) and ASTM C 1293 testing specifications.[5]

Results showed mitigation strategies able to control ASR distress with natural blue rock aggregate concrete.

RECYCLED BLUE ROCK AGGREGATE CONCRETE

Results from mitigation strategies with natural aggregate concrete were compared with like mixtures made with recycled aggregates. The recycled aggregate contained similar natural blue rock aggregate from the same aggregate quarry. Mitigation strategies were expected to control ASR distress as they did with blue rock aggregates. Problems with expansion failures were found to be directly related to the moisture swelling properties of the paste fraction of the RCA.

Identical recycled aggregate PCC mixtures, as made with natural blue rock aggregate, were made for comparison purposes with ASR expansion results. The recycled blue rock aggregate concrete conclusions are as follows.

Recycled Blue Rock Aggregate Concrete Initial Conclusions

1. Low alkali cement controlled ASR expansions, less than 0.04% at one year, with ASTM C 1293 standard prism beam testing.

2. Modified ASTM C 1293 prism beam testing showed 55% GGBFS cement substitution and 100% lithium nitrate mitigation controlled ASR expansion, less than 0.04% expansion at twenty-eight days.

3. ASTM C 1260 (mortar-bar method) testing is not applicable with recycled aggregate concrete due to preparation procedure. Pulverizing RCA destroys the aggregate/paste interface, which makes the material unique.

4. Modified ASTM C 1293 vacuum-sealed cube failure criteria, 0.04% expansion at fifty days, showed good correlation to standard ASTM C 1293 prism beam testing. Low alkali cement cube samples showed non-reactive results comparable to standard prism beam testing. One hundred percent lithium nitrate mitigation controlled ASR expansion below ASR selected limits; this result was not comparable to standard prism beam testing. All other mixtures showed failures with both standard prism beam and vacuum-sealed cube samples.

5. Electrical current introduction testing showed an increased rate of expansion when compared to standard ASTM C 1293 prism beam results, as seen with natural aggregate mixtures.

6. Standard ASR test applicability with the modified ASTM C 1293 prism beam testing procedure showed comparative results to standard test procedures.

7. ASTM C 1293 standard prism beam and vacuum-sealed cube samples showed high initial expansion values. This was not observed with natural aggregate concrete samples and was attributed to the moisture swelling properties of the paste fraction of the RCA.

The high initial expansions observed for all recycled aggregate concrete led to further research. The major difference between natural blue rock and recycled blue rock aggregate was the old paste fraction of the RCA, specifically its specific gravity and the high absorption percentage characteristic of the RCA. The high absorption allowed water to enter the paste fraction of the RCA, which caused expansion in the concrete samples during early hydration when the new matrix was soft. To counteract this process, aggregate saturation procedures were used to fill free water voids in the RCA before mixing. ASTM C 1260 testing did not have this problem as concrete samples were constantly submerged in solution, keeping aggregate free water voids full at all times and never allowing the voids to lose moisture. Recycled blue rock aggregate concrete saturated prior to mixing led to the following conclusions.

Recycled Blue Rock Aggregate Concrete Final Conclusions

Final conclusions were made after the use of saturation techniques to control early age expansion in recycled aggregate concrete mixtures.

1. The paste fraction of the recycled aggregate is directly related to initial moisture expansion that occurs during initial and early-age hydration.
2. Aggregate saturation processes can control recycled aggregate moisture gain expansion.

3. Initial ASR testing data with concretes having undergone saturation procedures showed a decrease in initial expansion characteristics from unsaturated aggregate concretes.

4. With initial aggregate preparation procedures, ASR distress can be controlled with presently used mitigation strategies, low alkali cement, 25% class F fly ash mitigation, and 100% lithium nitrate, in recycled aggregate PCC.

Recycled aggregate expansion data showed the absorption characteristics of an recycled aggregate must be addresses to ensure expansion is from ASR distress and not from the swelling of the paste fraction of the recycled aggregate from the introduction of water during mixing at early ages. ASR testing results showed presently accepted mitigation strategies are able to control ASR distress with recycled aggregate concrete.

PROJECT OBJECTIVES

Testing results showed recycled aggregate, having undergone ASR distress, was susceptible to ASR when introduced into new concrete mixtures. Presently accepted ASR mitigation strategies controlled ASR distress with recycled aggregate concrete. ASTM testing specifications, to determine ASR potential with aggregate and concrete mixtures, was applicable to recycled aggregate concrete. Modified ASTM testing procedures showed increased expansion rates when compared to standard testing data. This showed potential ASR distress data could be acquired in a faster manner than present testing procedures allow. Presently developed ASR mitigation guidelines for natural aggregate concrete mixtures controlled ASR potential with recycled aggregate concrete. All project objectives were evaluated and concluded in this study.

FUTURE RECOMMENDATIONS

1. ASR testing with recycled aggregate concrete must focus on material characteristics; including absorption percentage, percent paste fraction and the free alkali content of the RCA. This will provide information on the moisture expansion capability of the material and effects it may have to increase hydroxyl ion concentrations of concrete pore fluid; providing a more aggressive environment for ASR potential.
2. Modified ASTM C 1293 vacuum-sealed cube failure criteria, 0.04% expansion at fifty days, should be further studied as more data are necessary to prove the criteria is accurate and comparable to ASTM C 1293 standard prism beam data.
3. Modified ASTM C 1260 cube testing should be further investigated to develop failure criteria. It was concluded through this research that the cube shape provided a higher rate of expansion than the prism beam shape.
4. Procedure for demolding, pretreating and measuring cube samples should allow no moisture escape. The cube samples are very sensitive to moisture loss with a higher surface area compared to other samples tested. The moisture loss causes varying results and oscillations with graphed data. This problem was seen and documented in past research.[25]
5. Electrical testing, although showing increased expansion compared to ASTM C 1293 standard prism beam data, was not as effective as vacuum-sealed cube testing. The procedure to make the electrical current source, construct the cylinder test samples, construct cylindrical testing molds and find materials that can withstand the harsh environment within the testing molds was more difficult than the preparation for the vacuum-sealed cube procedure. Vacuum-sealed cube testing showed good comparison

with failure criteria in standard prism beam testing, while electrical data was random. Efforts should be targeted towards vacuum-sealed cube testing as the procedure is more user friendly and failure criteria are accurate with standard prism beam data.

6. Testing other sources of RCA would be beneficial to gather information on a broader range of aggregates with different mixture proportions.

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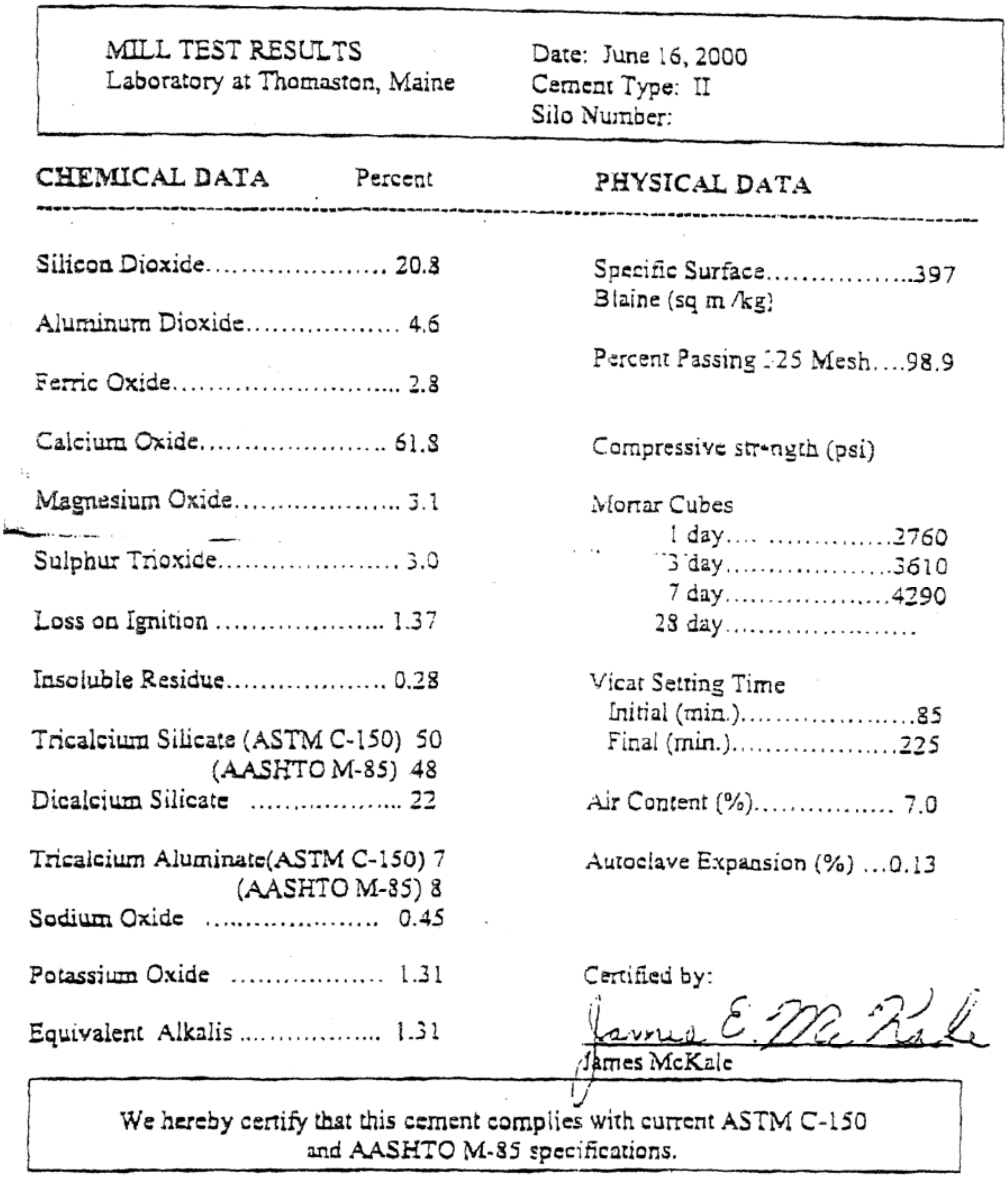
APPENDIX A: Mitigation Material Characteristics



MILL TEST RESULTS
Laboratory at Thomaston, Maine

Date: June 16, 2000
Cement Type: II
Silo Number:

CHEMICAL DATA	Percent
Silicon Dioxide	20.8
Aluminum Dioxide	4.6
Ferric Oxide	2.8
Calcium Oxide	61.8
Magnesium Oxide	3.1
Sulphur Trioxide	3.0
Loss on Ignition	1.37
Insoluble Residue	0.28
Tricalcium Silicate (ASTM C-150)	50
(AASHTO M-85)	48
Dicalcium Silicate	22
Tricalcium Aluminate(ASTM C-150)	7
(AASHTO M-85)	8
Sodium Oxide	0.45
Potassium Oxide	1.31
Equivalent Alkalis	1.31

PHYSICAL DATA	
Specific Surface Blaine (sq m /kg)	397
Percent Passing 325 Mesh	98.9
Compressive strength (psi)	
Mortar Cubes	
1 day	2760
3 day	3610
7 day	4290
28 day	
Vicat Setting Time	
Initial (min.)	85
Final (min.)	225
Air Content (%)	7.0
Autoclave Expansion (%)	0.13

Certified by:

James E. McKale
James McKale

We hereby certify that this cement complies with current ASTM C-150 and AASHTO M-85 specifications.

LAFARGE
NORTH AMERICA

Harleyville Operations
P.O. Box 326, Harleyville, South Carolina 29448

Cement

Consigned to	**Date**	
	Quantity	
	Type I	**Silo**
Identification No.	**Date(s) Ground** 1/1/02 - 7/10/02	

CHEMICAL TESTS

Al2O3	5.1	%
Fe2O3	3.5	%
MgO	1.1	%
SO3	2.8	%
Loss on Ign.	1.4	%
Insol. Res.	0.22	%
SiO2	20.7	%
C3S	60	%
C2S	14	%
C3A	8	%
Na2O Equiv.	0.26	%

PHYSICAL TESTS

Surface Area Blaine	379	m2/Kg
Autoclave Expansio	0.09	%
Vicat set Initial	1 : 28	Hrs:mins
Vicat set Final	3 : 23	Hrs:mins
Air Content	7.1	%

Compressive Strength	MPa	(PSI)
1 Day	14.9	2158
3 Day	24.9	3616
7 Day	34.4	4985
28 Day	48.0	6963

**The cement represented by this report meets:
APPLICABLE SCHD, NCHD, GAHD
VAHD SPECIFICATIONS and
ASTM C-150 STANDARD SPECIFICATIONS
FOR TYPE I CEMENT**

Quality Control Manager

LAFARGE
CORPORATION

Date: December 10, 2001

St-Constant Plant
Blended Hydraulic Cement (Silica Fume)

Period covered : November 1st / 30, 2001

Physical tests :

Spec.Surf. (Blaine) :		565	m2 / kg
Fineness (Sieve) 45 um :		92.1	%passing
Initial setting time :		105	minutes
Final setting time :		210	minutes
Autoclave Expansion :		0.07	%
Air Content:		9	%
Compressive strength at :	3 days :	3670	psi
	7 days :	5070	psi
October 1st / 31, 2001	28 days :	7180	psi

Chemical tests :

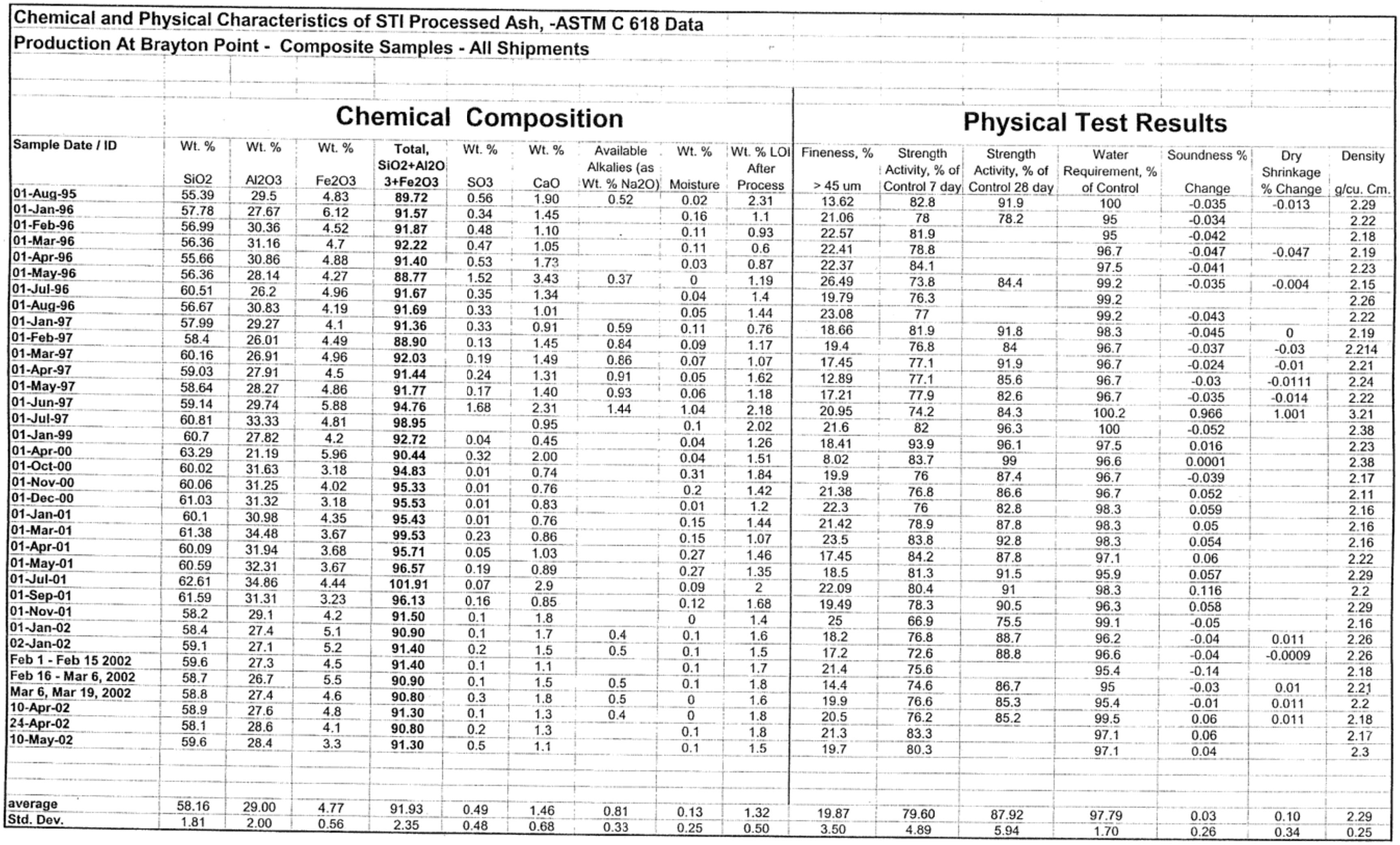
Silica (SiO2):	26.7	%
Alumina (Al2O3):	4.6	%
Iron Oxide (Fe2O3) :	2.1	%
Calcium Oxide (CaO) total :	58,5	%
Calcium Oxide (CaO) free :	0.4	%
Sulphur Trioxide (SO3) :	2.8	%
Magnesium Oxide (MgO) :	2.7	%
Alkali equivalent (Na2O) :	0.95	%
Loss on ignition :	0.9	%
Silica fume content (mass):	8	%

REFERENCE SPECIFICATIONS

We certify that the above cement, at the time of shipment, meets the chemical and physical requirements of the ASTM C1157-00 specification for both Type GU and Type HS.

Certified C. Lauzon
Claude Lauzon
Quality Manager

For any inquiry concerning this report,
please call our Technical Services at (514) 861-1411, ext. 233.



Chemical and Physical Characteristics of STI Processed Ash, -ASTM C 618 Data

Production At Brayton Point - Composite Samples - All Shipments

	Chemical Composition									Physical Test Results						
Sample Date / ID	Wt. % SiO2	Wt. % Al2O3	Wt. % Fe2O3	Total, SiO2+Al2O3+Fe2O3	Wt. % SO3	Wt. % CaO	Available Alkalies (as Wt. % Na2O)	Wt. % Moisture	Wt. % LOI After Process	Fineness, % > 45 um	Strength Activity, % of Control 7 day	Strength Activity, % of Control 28 day	Water Requirement, % of Control	Soundness % Change	Dry Shrinkage % Change	Density g/cu. Cm.
01-Aug-95	55.39	29.5	4.83	**89.72**	0.56	1.90	0.52	0.02	2.31	13.62	82.8	91.9	100	-0.035	-0.013	2.29
01-Jan-96	57.78	27.67	6.12	**91.57**	0.34	1.45		0.16	1.1	21.06	78	78.2	95	-0.034		2.22
01-Feb-96	56.99	30.36	4.52	**91.87**	0.48	1.10		0.11	0.93	22.57	81.9		95	-0.042		2.18
01-Mar-96	56.36	31.16	4.7	**92.22**	0.47	1.05		0.11	0.6	22.41	78.8		96.7	-0.047	-0.047	2.19
01-Apr-96	55.66	30.86	4.88	**91.40**	0.53	1.73		0.03	0.87	22.37	84.1		97.5	-0.041		2.23
01-May-96	56.36	28.14	4.27	**88.77**	1.52	3.43	0.37	0	1.19	26.49	73.8	84.4	99.2	-0.035	-0.004	2.15
01-Jul-96	60.51	26.2	4.96	**91.67**	0.35	1.34		0.04	1.4	19.79	76.3		99.2			2.26
01-Aug-96	56.67	30.83	4.19	**91.69**	0.33	1.01		0.05	1.44	23.08	77		99.2	-0.043		2.22
01-Jan-97	57.99	29.27	4.1	**91.36**	0.33	0.91	0.59	0.11	0.76	18.66	81.9	91.8	98.3	-0.045	0	2.19
01-Feb-97	58.4	26.01	4.49	**88.90**	0.13	1.45	0.84	0.09	1.17	19.4	76.8	84	96.7	-0.037	-0.03	2.214
01-Mar-97	60.16	26.91	4.96	**92.03**	0.19	1.49	0.86	0.07	1.07	17.45	77.1	91.9	96.7	-0.024	-0.01	2.21
01-Apr-97	59.03	27.91	4.5	**91.44**	0.24	1.31	0.91	0.05	1.62	12.89	77.1	85.6	96.7	-0.03	-0.0111	2.24
01-May-97	58.64	28.27	4.86	**91.77**	0.17	1.40	0.93	0.06	1.18	17.21	77.9	82.6	96.7	-0.035	-0.014	2.22
01-Jun-97	59.14	29.74	5.88	**94.76**	1.68	2.31	1.44	1.04	2.18	20.95	74.2	84.3	100.2	0.966	1.001	3.21
01-Jul-97	60.81	33.33	4.81	**98.95**		0.95		0.1	2.02	21.6	82	96.3	100	-0.052		2.38
01-Jan-99	60.7	27.82	4.2	**92.72**	0.04	0.45		0.04	1.26	18.41	93.9	96.1	97.5	0.016		2.23
01-Apr-00	63.29	21.19	5.96	**90.44**	0.32	2.00		0.04	1.51	8.02	83.7	99	96.6	0.0001		2.38
01-Oct-00	60.02	31.63	3.18	**94.83**	0.01	0.74		0.31	1.84	19.9	76	87.4	96.7	-0.039		2.17
01-Nov-00	60.06	31.25	4.02	**95.33**	0.01	0.76		0.2	1.42	21.38	76.8	86.6	96.7	0.052		2.11
01-Dec-00	61.03	31.32	3.18	**95.53**	0.01	0.83		0.01	1.2	22.3	76	82.8	98.3	0.059		2.16
01-Jan-01	60.1	30.98	4.35	**95.43**	0.01	0.76		0.15	1.44	21.42	78.9	87.8	98.3	0.05		2.16
01-Mar-01	61.38	34.48	3.67	**99.53**	0.23	0.86		0.15	1.07	23.5	83.8	92.8	98.3	0.054		2.16
01-Apr-01	60.09	31.94	3.68	**95.71**	0.05	1.03		0.27	1.46	17.45	84.2	87.8	97.1	0.06		2.22
01-May-01	60.59	32.31	3.67	**96.57**	0.19	0.89		0.27	1.35	18.5	81.3	91.5	95.9	0.057		2.29
01-Jul-01	62.61	34.86	4.44	**101.91**	0.07	2.9		0.09	2	22.09	80.4	91	98.3	0.116		2.2
01-Sep-01	61.59	31.31	3.23	**96.13**	0.16	0.85		0.12	1.68	19.49	78.3	90.5	96.3	0.058		2.29
01-Nov-01	58.2	29.1	4.2	**91.50**	0.1	1.8		0	1.4	25	66.9	75.5	99.1	-0.05		2.16
01-Jan-02	58.4	27.4	5.1	**90.90**	0.1	1.7	0.4	0.1	1.6	18.2	76.8	88.7	96.2	-0.04	0.011	2.26
02-Jan-02	59.1	27.1	5.2	**91.40**	0.2	1.5	0.5	0.1	1.5	17.2	72.6	88.8	96.6	-0.04	-0.0009	2.26
Feb 1 - Feb 15 2002	59.6	27.3	4.5	**91.40**	0.1	1.1		0.1	1.7	21.4	75.6		95.4	-0.14		2.18
Feb 16 - Mar 6, 2002	58.7	26.7	5.5	**90.90**	0.1	1.5	0.5	0.1	1.8	14.4	74.6	86.7	95	-0.03	0.01	2.21
Mar 6, Mar 19, 2002	58.8	27.4	4.6	**90.80**	0.3	1.8	0.5	0	1.6	19.9	76.6	85.3	95.4	-0.01	0.011	2.2
10-Apr-02	58.9	27.6	4.8	**91.30**	0.1	1.3	0.4	0	1.8	20.5	76.2	85.2	99.5	0.06	0.011	2.18
24-Apr-02	58.1	28.6	4.1	**90.80**	0.2	1.3		0.1	1.8	21.3	83.3		97.1	0.06		2.17
10-May-02	59.6	28.4	3.3	**91.30**	0.5	1.1		0.1	1.5	19.7	80.3		97.1	0.04		2.3
average	58.16	29.00	4.77	91.93	0.49	1.46	0.81	0.13	1.32	19.87	79.60	87.92	97.79	0.03	0.10	2.29
Std. Dev.	1.81	2.00	0.56	2.35	0.48	0.68	0.33	0.25	0.50	3.50	4.89	5.94	1.70	0.26	0.34	0.25