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EFFECTS OF INTERNAL EXPANSION REACTIONS ON THE MECHANICAL PROPERTIES OF CONCRETE

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To God and my family.

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"I have fought the good fight,
I have finished my course,
I have kept the faith.
Now there is laid up for me the crown of righteousness,
which the Lord, the righteous Judge,
will give me on that day;
and not to me only,
but also to all who love his coming"

2 Timóteo 4:7-8

ABSTRACT

LUCENA, M. E. M. F. G. **Effects of Internal Expansion Reactions on the Mechanical Properties of Concrete.** 2023. 84p. Engineering Master's Thesis in Civil Engineering Graduate School, Catholic University of Pernambuco, Recife, Brazil.

Among the various deleterious actions that can attack concrete elements is the alkali-aggregate reaction (AAR), which mainly affects the structures of dams, bridges and foundations, the most recurrent of which is the alkali-silica reaction (ASR). Due to the early deterioration of concrete in residential buildings and bridges in the Metropolitan Region of Recife, scientific studies have been carried out over the last decade to find out how this process works, with the aim of developing measures that can provide an acceptable level of performance and durability, in accordance with the regulations in use. One of the main challenges in predicting this phenomenon is understanding how the mechanical properties of concrete are affected, which is the subject of this research. In this master's research, samples made in the laboratory were tested to evaluate the ASR and its effect on the mechanical properties of the concrete samples. The tests carried out were compressive strength, static modulus of elasticity of the concrete and tensile strength, using different cements: CPIV and CPV. Visually, it was possible to identify some cracks on the surfaces of the samples and traces of silica gel. The values of the concrete's mechanical properties showed different results: the concrete's compressive strength was little reduced by the reaction. On the other hand, the static modulus of elasticity was significantly reduced by 35% and 38% for each cement respectively. The tensile strength was reduced by 9% and 30%, but these results must be analyzed carefully, given the conditions in which they were tested. Therefore, the method used to create artificial ASR proved to be effective and has the potential to be used in further ASR studies. The modulus of elasticity also proved to be the most suitable tool for detecting the presence of ASR.

Keywords: concrete; durability; alkali-aggregate reaction; alkali-silica reaction; compressive strength; tensile strength; modulus of elasticity.

RESUMO

LUCENA, M. E. M. F. G. **Efeitos das Reações de Expansão Interna nas Propriedades Mecânicas do Concreto.** 2023. 84p. Dissertação de Mestrado em Engenharia Civil, Universidade Católica de Pernambuco, Recife, Brasil.

Dentre as diversas ações deletérias que podem atacar os elementos de concreto está a reação álcali-agregado (RAA), que atinge principalmente as estruturas de barragens, pontes e fundações, sendo a mais recorrente a reação álcalis-sílica (RAS). Devido à deterioração precoce do concreto em edifícios residenciais e pontes na Região Metropolitana do Recife, na última década foram realizados estudos científicos para conhecer o funcionamento desse processo, com o objetivo de desenvolver medidas que possam proporcionar um nível de desempenho e durabilidade aceitável, de acordo com as normas vigentes. Um dos principais desafios na previsão deste fenómeno é compreender como as propriedades mecânicas do concreto são afetadas, o que constitui o tema deste estudo. Nesta pesquisa de mestrado, foram ensaiadas amostras feitas em laboratório em um estudo anterior para avaliar a RAS e o seu efeito nas propriedades mecânicas das amostras de concreto. Os ensaios realizados foram de resistência à compressão, módulo de elasticidade estático do concreto e resistência à tração, utilizando-se diferentes cimentos: CPIV e CPV. Visualmente, foi possível identificar algumas fissuras nas superfícies das amostras e vestígios de sílica gel. Os valores das propriedades mecânicas do concreto apresentaram resultados diferentes: a resistência à compressão do concreto foi pouco reduzida pela reação. Por outro lado, o módulo de elasticidade estático foi significativamente reduzido em 35% a 38% para cada cimento, respetivamente. A resistência à tração foi reduzida em 9% a 30%, mas estes resultados devem ser analisados com cuidado, dadas as condições em que foram ensaiados. Assim, o método utilizado para criar ASR artificial provou ser eficaz e tem potencial para ser utilizado em estudos posteriores de ASR. O módulo de elasticidade também se revelou a ferramenta mais adequada para detectar a presença de RAS.

SUMARY

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LIST OF ABBREVIATIONS AND ACRONYMS

AAR - Alkalis-Aggregate Reaction
ACR- Alkali-Carbonate Reaction
ACPT - Accelerated Concrete Prism Tests
AMBT - Accelerated Mortar Bar Tests
ASG - Alkali-Silica Gel
ASR - Alkali-Silica Reaction
CPT - Concrete Prism Tests
CPIV - Portland Cement Type IV
CPV - Portland Cement Type V
DEF - Delayed Ettringite Formation
EDX - Energy Dispersive X-Ray
FT - Freezing and thawing
ITZ - Interfacial Transition Zone
SEM - Scanning Electron Microscopy
XRD - X-Ray Diffraction

Chapter 1

1. Introduction

Alkalis-aggregate reaction (AAR) is an important issue in the Brazilian construction industry since this deleterious reaction has affected several structures and buildings. AAR was firstly public in Brazil in 1963 at Jupia´s dam. Since then, several AAR events have been reported in Dam and electric power plants, which represent the most concern regarding AAR in Brazil, mainly due to social, economic and environmental impact of those infrastructures.

The participation of the aggregate in the AAR takes place most of the time through silica. This mineral silicon dioxide can be found in rocks, sands, quartz, quartzite, and other materials. Thus, it is widespread in deposits worldwide, considering silicon is abundant in the earth’s crust. Brazil has a huge variety of rocks explored for use in concrete production. Due to their mineralogical characteristics, many Brazilian rocks have a reactive potential, mainly due to the strong presence of silica and/or silicates in their composition.

The choice of aggregate for concrete structures is a great responsibility and should not be neglected. Even though the raw materials’ selection should consider the aggregate quality and adequacy for a certain application, it mostly depends on the local availability for economic reasons. Thus, an effective way to evaluate ASR susceptibility on concrete aggregates and predict or prevent the in situ behavior of the final concrete product properties is crucial. This is particularly valid when quartz mineral is present in aggregate source. Even though it is generally not reactive, the geological origin represents distinctions regarding ASR reactivity. When the source rock undergoes some stress, that is, pressure due to tectonic movements, dynamic metamorphism occurs, called cataclase. This process causes the rocks to be crushed and fragmented, and then the tensed quartz appears, which is reactive. From tectonic movements, geological faults arise, where tensioned quartz is widely found.

The state of Pernambuco has one big and well-known flaw, the Pernambuco East Shear Zone (ZCPE). Figure 1 illustrates the main fault zones existing in the state of Pernambuco. This geological factor, added to the high level of the water table, makes Recife a very prone city to suffer from ASR.

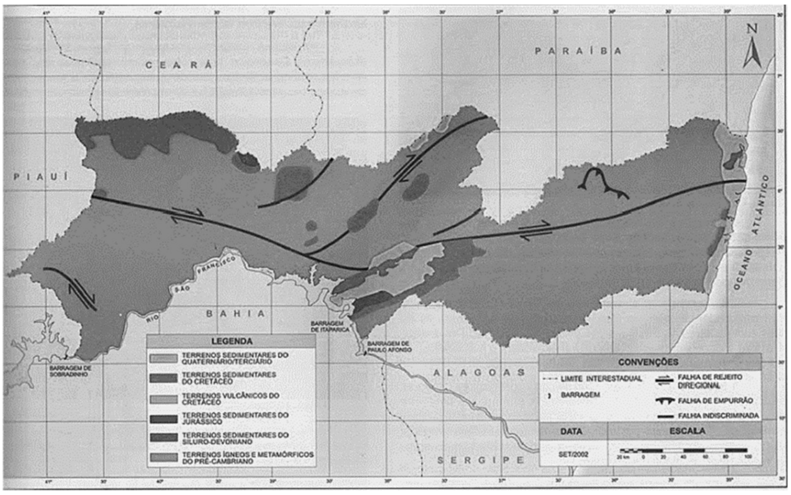


Figure 1 - Pernambuco East Shear Zone (adapted from [86]).

The Portland cement (PC) patent in 1824 revolute the construction industry world, and PC concrete materials became the most widely manufactured materials in the world. With the significant growth of the ready-mixed and precast concrete industries over the past 60 years, concrete performance requirements have become very demanding, such as higher early strength, flowability/self-compactability, durability, and, more recently, ecological footprint concerns. The unsatisfactory durability of vast numbers of concrete structures built then provoked significant concern among the construction stakeholders and the scientific community.

Alkali-aggregate reaction (AAR) is a major concrete durability issue. Deleterious expansions associated with AAR have been reported among the main causes of deterioration of important concrete structures and infrastructures, such as dams and hydraulic structures, pavements, bridges, walls, barriers, and nuclear/power plants. This expansive deleterious reaction motivated by ASR can gradually reduce the service life, the load-carrying capacity and the safety of the concrete structures. This may result in a costly high replacement or even the demolition of the structure. [82] [95] [96] [97] [98] [99]. Two AAR types can occur - Alkali-silica reaction (ASR) that develops due to reactive silica minerals present in some natural aggregate and Alkali carbonate reaction (ACR) triggered by aggregate particles containing carbonate or dolomite [94].

Silica can be found in most natural aggregates, and thus ASR is the most common type of AAR occurrence. In brief, the ASR is a reaction between highly alkaline pore solutions from PC hydration (K+, Na+, OH–) with certain aggregates which contain a reactive form of silica. This reaction produces hygroscopic silica gel that can absorb water and swell, thus generating stress. It will manifest as extensive expansion and can lead to cracking, aggregates pop-out, gel exudation, and harmful white deposits on the concrete surface. ASR phenomena take place when a combination of conditions are verified namely: Aggregates with a certain amount of reactive siliceous minerals; Rich concrete pore solution, High moisture and calcium ions available.

Nevertheless, ASR is a slowly expansive reaction, and it can take 10–15 years to manifest in concrete structures or elements. Even though the in-service performance of an aggregate is considered the most reliable method to assess the aggregate alkali reactivity, it is not suitable. Besides, the “in service” performance of a certain aggregate depends on several factors, such as the exposure conditions of the structure or element, the alkali content of the concrete mixture employed, the aggregates used, the type of structure, etc. Thus, to ensure that a certain type of aggregate is suitable for concrete production, ASR potential must be assessed before being incorporated into the concrete mix. The need to obtain information about the concrete aggregate reactivity in a short period and before being employed in a real project forced the adoption of accelerated and reproducible ASR test methods.

In fact, ASR has been under investigation over the last century, since Stanton's pioneering work in 1940. Even though several test methods have been established to evaluate aggregates' ASR susceptibility, a fast and effective method for ASR assessment may not yet be defined, and, in most cases, a set of tests is adopted to verify the reactivity of the aggregate. The tests for evaluating the AAR can be classified into two types:

- Methods that only assess the aggregate, such as petrographic examination, chemical method, Osipov method, scanning electron microscopy;
- Methods that evaluate the composite (cement + aggregates or cement + SCM + aggregates) behavior when exposed to an environment that favors ASR occurrence that relies on expansion indicator, such as Accelerated Mortar Bar Tests (AMBT), Concrete Prism Tests (CPT) and Accelerated Concrete Prism Tests (ACPT).

Even though AAR impact is under scrutiny by universities and research centers in the country, the first national standard was only issued in 2018 by the Brazilian Association for Standardization (ABNT), using the Brazilian code NBR 15577 – Aggregates: Alkali-Aggregate Reactivity [1]

Specifically, in Recife, due to the low level of the land in relation to sea level, the buildings are subject to humidity and water, which is an important cause of internal swelling reaction and particularly ASR. In the end, the premature deterioration of building foundations often entails a large cost for companies to carry out repairs and restoration work. Companies need to ensure the safety of their customers, as well as remaining profitable in relation to repair costs. in relation to repair costs.

A structure must resist over time to the various aggressions or solicitations (physical, mechanical, chemical, etc.) i.e. to the loads to which it is subjected, as well as to the various actions such as the wind, the rain, the cold, the heat, the humidity, the ambient environment, etc. while preserving its aestheticism. It must satisfy, with a constant level, the needs of the users during its lifespan. Designing a durable concrete requires that all the environmental constraints and potential aggressions that it will be exposed to throughout its lifetime be considered at the design stage, and that the recommendations in use are respected and carried out.

This work aims to contribute to the knowledge regarding ASR that will allow the construction of buildings and concrete structures with an increased durability and compatibility with the Brazilian code and actual performance requirements. In order to do that, it is important to have relevant information on the mechanical response. The study and analysis of the behavior of mechanical properties using compressive strength test, tensile strength test, modulus of elasticity test will be performed on specimens of concrete undergoing ASR.

1.1 Research Significance

Concrete, a fundamental building material, plays an important role in the construction industry due to its durability and versatility. Over the years, researchers have explored various aspects of concrete's properties to improve its performance and lifespan. One critical area of investigation involves understanding the effects of internal expansive reactions on the strength and deformation properties of concrete. This research is of paramount importance as it directly influences the structural integrity, safety, and durability of concrete structures.

Internal expansive reactions in concrete refer to the chemical processes that result in volume changes within the material. Such reactions can be attributed to factors like alkali-silica reaction (ASR), delayed ettringite formation (DEF), or hydration of certain expansive cements. The consequences of these reactions extend beyond mere volumetric changes; they significantly impact the mechanical properties of concrete, including strength and deformation characteristics.

In recent years, the construction industry has faced new challenges related to sustainability, environmental impact, and the demand for high-performance materials. As a response, researchers have intensified their efforts to explore eco-friendly alternatives and optimize traditional materials. Internal expansive reactions in concrete have gained renewed attention in this context, as they directly influence the service life and performance of concrete structures.

Recent studies have elucidated the intricate mechanisms of internal expansive reactions and their correlation with concrete properties. For instance, researchers has demonstrated the influence of ASR on the microstructure of concrete, highlighting its direct link to reduced compressive strength and increased deformability. Some previous works shed light on the role of DEF in causing internal stresses, leading to cracking and deterioration of mechanical properties.

Understanding the impact of internal expansive reactions on concrete properties is crucial for developing effective mitigation strategies. Incorporating supplementary cementitious materials, employing expansive additives judiciously, and optimizing mix designs are among the proposed solutions. Moreover, the development of advanced testing techniques, such as non-destructive methods and high-resolution imaging, has enabled researchers to monitor internal expansive reactions in real-time and assess their influence on concrete performance.

In summary, ongoing research into the effects of internal expansive reactions on the strength and deformation properties of concrete is indispensable for addressing contemporary challenges in the construction industry. By elucidating the underlying mechanisms and proposing mitigation strategies, scientists contribute to the development of durable and sustainable concrete structures. As the field continues to evolve, collaboration between researchers, engineers, and industry professionals remains essential to ensure the practical implementation of findings and the advancement of concrete technology.

1.2 Research Objectives

The general objective of the master research is to analyze the effects of internal expansive reactions on the tensile strength, compressive strength and static modulus of elasticity of standardized concrete specimens. This objective is detailed below:

- Prepare a sufficiently representative quantity of standardized concrete specimens and subject them to an environment that favors the creation of internal expansive reactions in the laboratory;
- Perform chemical tests in fine and coarse aggregate to determine their reactivity;
- Perform physical and chemical analysis of the concrete microstructure using scanning electron microscopy (SEM) associated with energy dispersive X-ray (EDX), X-ray diffraction (XRD) and Raman spectroscopy in concrete samples;
- To thoroughly characterize a solid concrete structure degraded by internal swelling reactions, through advanced tests, trying to correlate the problem in the field with the characteristics found in the laboratory tests;
- Carry out standardized compressive strength, tensile strength and static modulus of elasticity tests on all the specimens produced affected and no affected by expansion reactions.

1.3 Organization of the Dissertation

The Dissertation is organized in 6 (six) chapters. This first one presents the introduction, the statement of the research theme and its justification, the statement of the general objective and the specific objectives, the delimitations of the work and the organization of the dissertation.

Chapter 2 presents the bibliographic review on the internal swelling reactions, types and behavior. As well as a review of the concrete mechanical, transport and physical-chemical properties and characteristics.

Chapter 3 presents the description of the methodology used to develop the research in order to formulate the hypotheses to the diagnosis of the early deterioration of the concrete pile cap block from where the samples were collected.

Chapter 4 presents the results obtained through the experimental program performed as well as the complete discussion regarding the correlation of this results with the pathological manifestation observed in the pile cap block investigated.

Chapter 5 presents the conclusions drawn from the research performed as well as recommendations for future works.

Chapter 6 there contains the bibliographic references used in the development of the research.

Chapter 2

2. Literature Review

Concrete is a complex substance made up of a cement matrix, an interfacial transition zone, and aggregate. Some studies [2-4] estimate that the typical thickness of the interfacial transition zone (ITZ) is 15-50 lm. Because of the huge number of calcium hydroxide and needle-shaped ettringite crystals in the open pores of the transition zone, it is regarded the weakest phase of concrete [2].

A hardened concrete construction must have a lengthy service life in order to be durable. Several phenomena can have an impact on its performance. These attacks can be chemical, physical, mechanical, electrochemical, or biological, and two or more of them can act at the same time. External sulfate attack, delayed hydration of free calcium oxide (CaO) and free periclase (MgO), also known as delayed ettringite formation (DEF), alkali-aggregate reaction (AAR), and corrosion of concrete reinforcement are the chemical reactions that include the formation of expansive products [3].

Sulphates can come from a variety of sources, including biological, natural, and even air pollution. The following are some potential origins:

- If groundwater comes into contact with sulfates;
- Alluvial or clay soils may also contain pyrites, which oxidize to sulfates when exposed to air and moisture, forming sulfuric acid;
- Aerobic biological decomposition of industrial products such as fertilizer and;
- Sulfates can also be obtained directly from the aggregate used.

These are some of the sulfates that cause this reaction at specific concentrations: $CaSO_4$, $MgSO_4.6H_2O$, K_2SO_4, Na_2SO_4, and $Na_2SO_4.10H_2O$.

The fact that it has several characteristics that trigger an expanding reaction in concrete makes it a complex phenomenon. Ph level, outside temperature, outside sulfate concentration, w/c ratio, and clinker composition are other variables that are significant in the onset of the reaction and its changes over time. Figure 2 below shows a schematic view of sulfate attack on concrete where it can be seen that the primary ingredients of cement paste is $Ca(OH)_2$, an element that leads to DEF. The salt of sulfates results in the production of expansive products. Ultimately, it results in a mesh network of numerous tiny cracks arranged throughout the concrete.

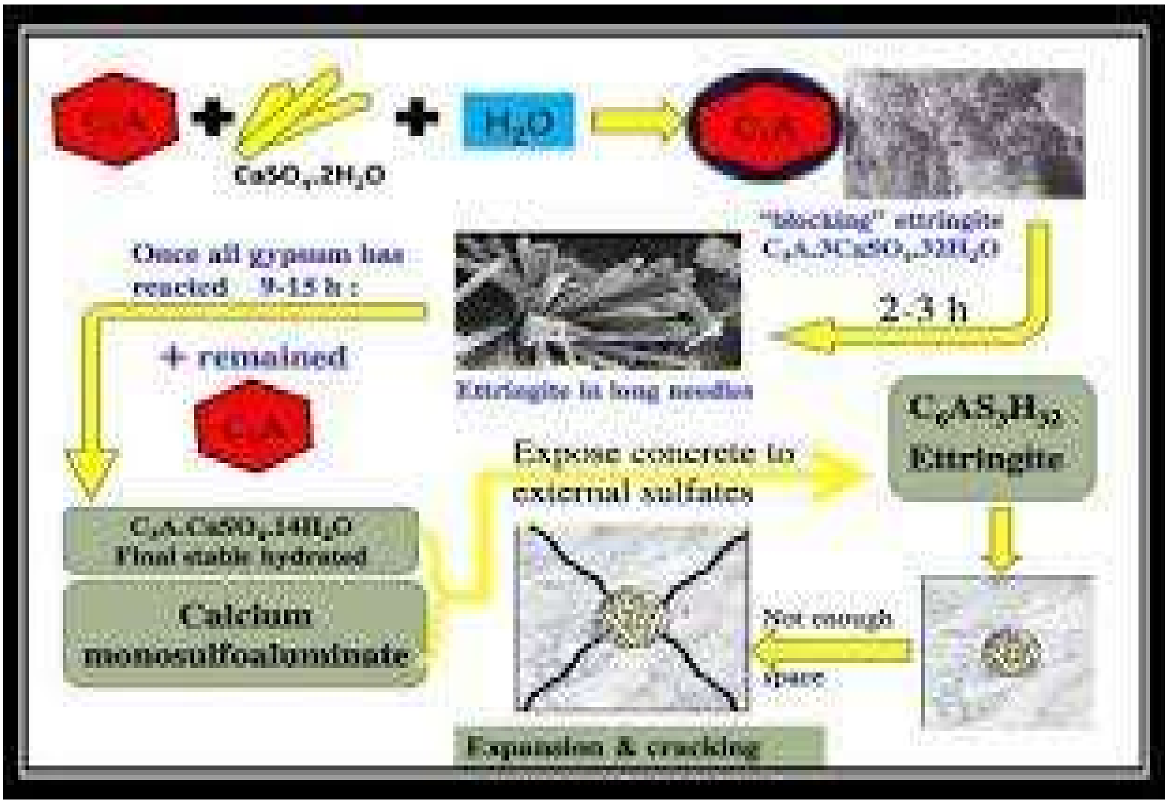


Figure 2 - Description of the sulphate attack process and production of delayed ettringite formation.

For concrete to be able to withstand the typical stresses and deformation applied to it, it needs to be impermeable and compact. Furthermore, the graph below by [74] shows a direct relationship between the swelling brought on by the sulfate attack and the cement's concentration of tricalcium aluminate (C_3A). Therefore, the type of cement used will determine how concrete behaves in a sulfate environment. Porous concrete (low cement content) can be vulnerable, but only if the C_3A content of the cement is low. Figure 3 exhibits this behavior.

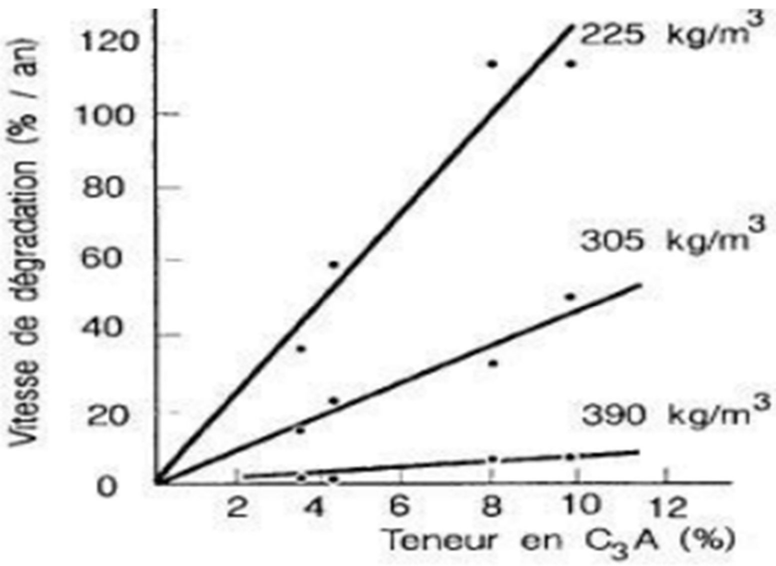


Figure 3 - Influence of cement dosage and C3A content on the rate of concrete degradation of concrete (16 years in 10% Na2SO4).

The remobilization of sulfates that were originally present in the cement matrix as a result of overheating the concrete when it was still young can also cause the internal sulfate reaction. Here, we are discussing the delayed ettringite development. This phenomenon occurs in concretes that have a sensitive composition, meaning they contain high levels of SO_3, C_3A, and Na_2O equivalent, siliceous or silicate aggregates, and are in the initial stages of micro cracking. These concretes are also subjected to a long-term favorable environment, which includes sufficiently high humidity and temperatures that are higher than 60 - 70 °C.

Dicalcium silicate (C_2S), tricalcium silicate (C_3S), tricalcium aluminate (C_3A), and tetracalcium ferroaluminate (C_4AF) are the four primary constituents of cement. On the other hand, silicates and aluminates are not the sole chemical components found in industrial Portland cements. Numerous elements and contaminants, including sulfur, magnesium, sodium, and potassium, are integrated into these compounds during the manufacture of clinker and may be hazardous if present in excessive levels [4].

When cement is hydrated in the presence of water from the start of the hardening process, some amount of heat is released. Because of the limited thermal conductivity of concrete, this heat dissipates slowly, particularly when huge volumes of concrete are being placed. For large structures, the resulting heating can be substantial, but for thin components with a high surface/volume ratio, it is insignificant. The fastest chemical reactions occur during the hardening phase, during which the concrete's temperature reaches its peak and then progressively drops.

The primary ettringite is created shortly after C_3A hydrates, and it does not do any harm to concrete. On the other hand, secondary, or "delayed ettringite," encourages structural expansions and fractures. The concentration of aluminate ions in the solution and the quantity of sulfate ions present determine the ettringite mineral, also known as hydrated calcium trisulfoaluminate [4].

One type of heat-induced sulfate attack is DEF. The expansion of the cement paste in the presence of moisture is a characteristic of this reaction. High temperatures during the curing process will speed up the natural occurrence of ettringite production in the concrete, causing massive expansions and widespread cracking when the ettringite reassembles in the hardened concrete.

Compared to AAR, DEF is a relatively uncommon occurrence, but its ramifications are far more profound. The most vulnerable constructions to this kind of response are usually thought to be mass concrete structures and heat-cured precast parts. This phenomenon is also more complicated because it is influenced by a number of variables, including the clinker's composition, the W/C ratio, the external temperature, and the concentration of sulphates outside. The following can be used to summarize a few solutions to these issues - the addition of minerals which enables the reduction of cement and, consequently, C_3A; the strength of concrete is increased by silica fumes and flying ashes and controlling the temperature during the mixing process.

A chemical reaction known as the alkali-aggregate reaction (AAR) occurs when certain mineral phases from the aggregates and alkali hydroxides from the concrete pore solution come into contact.

As a result of a chemical reaction between the alkali hydroxides dissolved in the concrete pore solution and "unstable" silica mineral forms within the aggregate materials, such as chert, quartzite stressed by earthquakes or geological faults, opal, and strained quartz crystals, alkali-silica reaction (ASR) is by far the most prevalent type of AAR found worldwide. When moisture is taken up from the surrounding environment, it produces a secondary gel that causes expansive pressures to be created inside the reacting aggregate material(s) and the nearby cement paste. There is some disagreement about whether alkali-carbonate reaction (ACR), a somewhat less prevalent type of concrete distress, may be classified as an ASR [5].

A gel is created, and as it absorbs water, it grows larger and applies expanding pressure, which causes the concrete to break. ASR results in the typical "map cracking" or "Isle of Map cracking" in unrestrained concrete, or concrete without any reinforcement. A few years after the concrete has dried, the gradual process can begin. The amount of time needed to cause noticeable wear in the concrete owing to AAR can range from two to more than twenty-five years, depending on variables including the alkali level of the concrete, the kind of reactive mineral form present in the fine and/or coarse aggregate, and the availability of moisture.

When reactive forms of silica are present at expansive locations within aggregate particles, micro cracks linked to ASR are produced. The interfacial transition zone (ITZ), the cement paste, and the aggregate particles are all affected by the cracks, which spread between and through them. The secondary reaction products that result are alkali-silica gel. When ASR gel swells in the presence of water, the bulk concrete volume may experience micro cracking and severe pressure [6].

Fracture mechanics generally controls the formation and propagation of cracks brought on by ASR. A material releases significant amounts of energy during loading and deformation processes when it exhibits imperfections, flaws, or cracks [7].

Therefore, when the energy released exceeds the fracture energy required to propagate the break, the crack begins to spread. Furthermore, cracks typically spread in areas where elastic energy is released with little to no fracture energy used. As a result, in order to spread out, cracks will always select their preferred paths, which are typically the interfacial transition zone (ITZ) in the case of mortar and concrete or the lowest distance in the case of a homogenous medium like cement paste. Whether the energy released through the particles is less than through the ITZ, cracks may occasionally bypass the aggregate particles entirely [8]. The features of the damage differ based on the kind of distress mechanism, as it shown in Figure 4. Though little is known about how different damage characteristics affect the mechanical properties and durability of the affected concrete, characteristics like crack "pattern" and "extent" suggest important information about the type of ISR mechanism and the degree of damage associated with a deterioration process. Because of the spread of micro cracks through or around the aggregate particles and/or cement paste, the internal expansion that takes place in structures impacted by ASR is typically linked to a change in the mechanical properties of the concrete material [9-12].

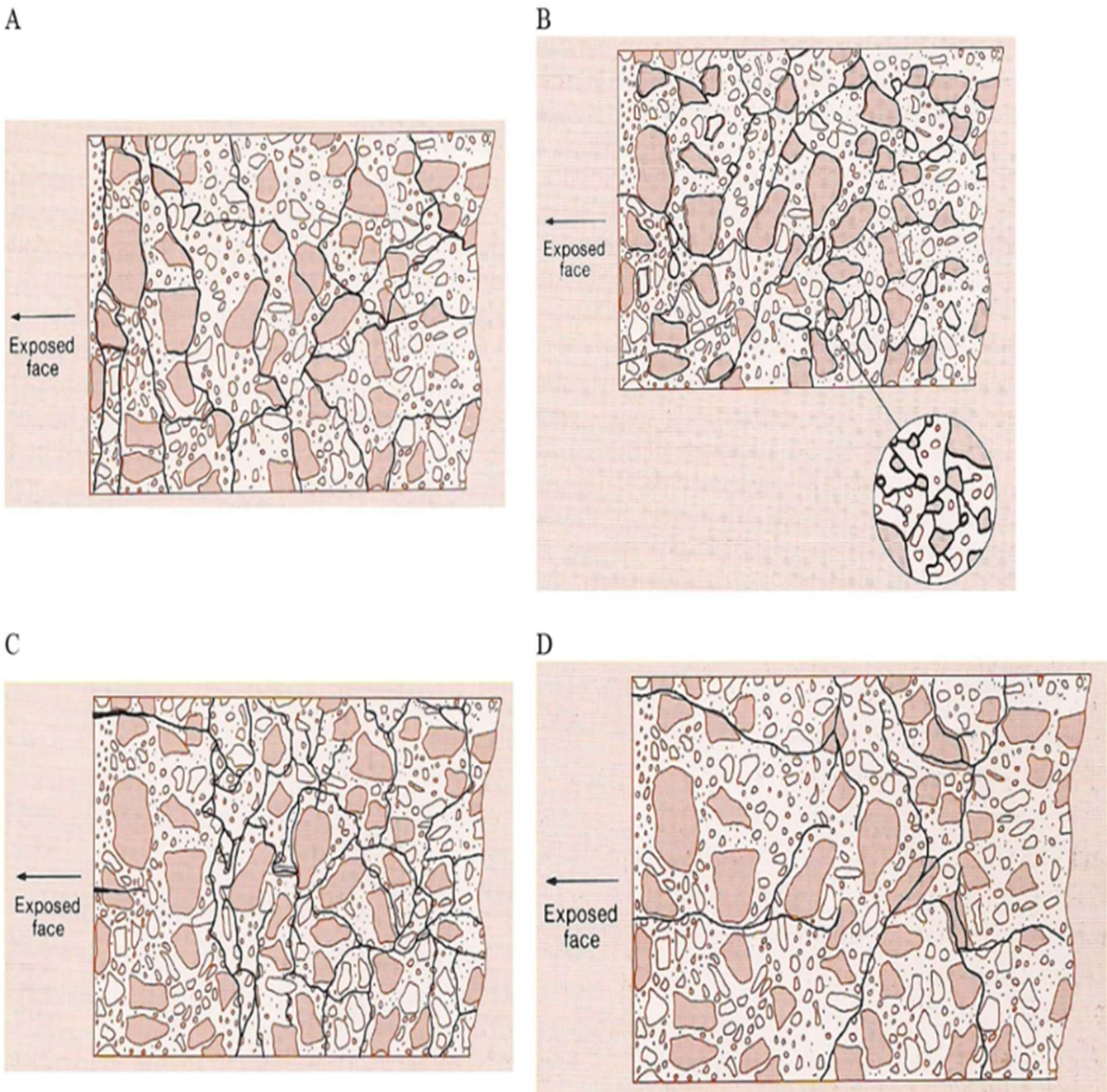


Figure 4 - Internal cracking caused by different mechanisms - Freezing and thawing action, (b) Delayed ettringite formation, (c)ASR from fine reactive aggregate and (d) ASR from reactive coarse aggregate [8].

Geometry, confinement, reinforcement ratio and configuration, gradients and localized stress concentrations, and the distribution of applied loading are among the variables that affect structural concrete elements [13-14].

In addition, temperature changes, moisture effects, environmental factors, and other damage mechanisms like corrosion and freeze-thaw cycles affect them [14-17]. These factors also include chemical prestressing, size effects, boundary conditions, and loading history.

According to previous works, the nature and type (fine vs. coarse) of the reactive aggregates used in the mixture as well as the concrete strength influence the mechanical responses of the affected materials. Consequently, results may differ based on these parameters.

The silica found in the majority of concrete aggregate types reacts chemically with the hydroxide ions in the concrete pore fluid. The likelihood of the alkali-silica reaction (ASR) is raised by the higher pH caused by the increased concentration of hydroxide ions [18-21]. A silanol[1] (Si–O–H) bond is formed when the siloxane bridge bursts and silica dissolves at high pH values. In addition to the pH of the pore fluid, other factors that influence the dissolving rate of silica include temperature, the silica particle size, and the concentration of cations (Na+, K+, and Ca^{2+}).

Alkali-silica gel (ASG) is a hygroscopic gel that is produced by the alkali-silica reaction (ASR). When the reactive silica in the aggregate is dissolved by the alkali hydroxides in the concrete's pore solution, the ASR begins. ASG is created when the alkali hydroxides and dissolved silica combine. The microcracks can then provide pathways for water to enter the concrete, which can further accelerate the ASR and ASG formation. The ASG experiences internal tensions and swells as a result of absorbing moisture. Cracks through the surrounding cement paste and aggregate particles will result from these stresses. As such, concrete members will be susceptible

[1] A silanol is a functional group in silicon chemistry with the connectivity Si–O–H. It is related to the hydroxy functional group (C–O–H) found in all alcohols.

to several types of damage in addition to decreases in strength (compressive, tensile, and bond), stiffness, modulus of elasticity, and increases in porosity and permeability.

2.1 Effects of Internal Expansive Reactions on Concrete Properties

The manifestation of alkali-silica reaction (ASR) has the potential to modify the mechanical characteristics of concrete by inducing alterations in its internal structure and giving rise to delayed cracks [22].

Numerous investigations have delved into the impact of ASR on various mechanical properties of concrete, encompassing compressive strength, modulus of elasticity, flexural strength (modulus of rupture), and tensile strength [23-25]. The outcomes of these studies have consistently shown that ASR can markedly diminish the engineering properties of concrete. However, the extent of reduction is not uniform across all properties. Despite the increasing volume of research addressing ASR and its effects on mechanical properties, there remains a gap in understanding the precise determination of these properties under ASR conditions. For instance, studies have reported a substantial reduction in tensile strength and modulus of elasticity due to ASR [26,27], while findings related to compressive strength have yielded inconclusive results [28-29]. These variations may be attributed to differences in experimental conditions, specimen dimensions, types of specimens, and the reactivity degrees of aggregates in the conducted studies.

2.1.1 Compressive Strength

According to [30], compressive strength is typically not a reliable measure of ISR-induced damage, particularly when there are AARs in the concrete.

Concrete, especially in the case of ASR, can bear a significant amount of compressive stress even in the presence of a large number of micro cracks. Even at modest expansion levels, the concrete's compressive strength can remain relatively similar to the original design strength.

This information is connected to the microscopic damage traits of AAR, which primarily occur inside the aggregate particles [9].

However, in the case of DEF, the pattern of its distress features, which are mostly found in the cement paste and the ITZ, results in notable losses in compressive strengths of up to 80% at high and very high free expansion levels [10, 12].

The effect of ASR on the compressive strength of concrete is a function of time. It has been found that compressive strength decreases as damage due to the reaction increases at the micro-structural level.

Many researchers [31-34] reported that the loss in compressive strength can be as high as 40–60% with a reduction of 20% being likely to occur for expansions found in practice.

Previous work [35] indicated that the compressive strength losses were highly dependent on a number of variables, none of which were repeated in the previous research, including mix design, aggregate type, and storage circumstances. Nonetheless, the broad patterns noticed are relevant. Investigations were conducted on the secant modulus of elasticity (E) and the cylinder compressive strength (fc_0) at various exposure times. The main results reported by [36] are as follows: (a) The normal strength concrete that was made with the highly reactive particles showed the greatest drop in compressive strength. After 12 weeks of exposure, specimens exposed to NaOH solution showed an overall decrease in their compressive strength of 24% and their elastic modulus of 81%. After the same exposure duration, a 14% overall strength increase was noted in the specimens kept in de-ionized water; (b) Still considering usual concrete strengths, the compressive strength of the specimens over a 12-week period remained essentially the same for those exposed to the NaOH solution and with somewhat reactive aggregates.

According to [37], apud [15], compressive strength is little influenced by the internal expansion reaction ASR, considering high expansion levels (0,30%). The concrete exhibits compressive strength loss of around (0,29 to 0,43%) when it has DEF combined with ASR or only DEF acting solely.

2.1.2 Tensile Strength

Another important component of ASR is the generation of internal tensile strength in concrete as a result of gel swelling. Tensile strength is without a doubt the most vulnerable aspect of concrete. As a result, creating an internal tensile force can readily affect the tensile strength of concrete, which might be hazardous. Investigations about the influence of ASR on the mechanical characteristics of concrete reported that all appraised properties decrease due to ASR [38]. Tensile strength showed the highest susceptibility to ASR and experienced the greatest drop, with the primary reduction appearing at three days.

Some authors studied the behavior of regular and high strength concrete specimens in direct tension. Uniaxial tests are often used to determine the stress-strain relationship because they more accurately describe the mechanical behavior of concrete in tension, shear, and bond than indirect tension tests [39-40].

[39] also observed that the direct tensile strength of high strength concrete was 4-5% of fc_0. The direct tensile strength of normal strength concrete sample was found to be approximately 8-10% of fc0. The direct tension test findings are more susceptible to changes in the C-S-H gel than the compressive strength tests.

ISR-induced damage has a more dramatic influence on direct tensile strength and can result in considerable strength decreases [30-14]. It is crucial to note that evaluating the tensile strength of concrete is a difficult undertaking because different test methodologies produce varied findings.

Splitting tensile tests are typically ineffective in representing tensile strength losses in ISR-affected concrete, and direct tensile strength tests, such as the gas pressure tension test, should be done whenever possible [41].

Previous work [42] indicated that, after 12 weeks of exposure, the tensile strength of normal strength concrete specimens containing either highly reactive aggregates or moderately reactive aggregates decreased. Tensile strength dropped by 37% and 31% in specimens made with moderately reactive extremely reactive and moderately reactive aggregates, respectively, when exposed to NaOH solution. Tensile strength was not reduced in specimens made with moderately reactive aggregates and placed in deionized water for 12 weeks. Specimens constructed with highly reactive aggregates, on the other hand, exhibited a 7% loss in tensile strength throughout a 12-week testing period. This minor drop can be attributed to the significant variability of concrete tensile strength values.

Smaoui et al. [43] conducted considerable study on the influence of ASR on the mechanical characteristics of concrete and concluded that all appraised properties decrease owing to ASR. Tensile strength showed the highest susceptibility to ASR and experienced the greatest drop, with the primary reduction appearing at three days. Several studies have shown that tensile strength decreases before significant expansion occurs. This phenomenon is related to the nature of the tensile strength loss caused by the produced micro-cracks [44,45].

Previous investigations indicated that the type of combination and the test procedures have a major impact on the tensile strength results. The cylinder splitting test, according to Jones and Clark [34], is less susceptible to the influence of ASR than the other tests since it generates failure along a preset line. This test is very easily influenced by the position and orientation of surface cracking.

2.1.3 Static Modulus of Elasticity

The static modulus of elasticity is more sensitive to the effects of internal expansion responses than the compressive strength, according to Sanchez et al. and Hasparyk in [46-48]. The presence of DEF or ettringite mixed with ASR in concrete causes stiffness loss ranging from 50 to 65%, and when just ASR is present, the decrease in static elasticity modulus values can reach 67% [48]. Through DEF, reactive aggregates can also contribute to the concrete expansion process [49].

Giaccio et al. [50] used the long-term ASTM C1293 test to determine compressive strength and modulus of elasticity. They demonstrated that compressive strength was impacted, but the rate of change fluctuated and was not consistent. This unstable behavior is caused by internal alterations and the ability to overcome the hydration reaction to ASR, which enables it to develop strength. The modulus of elasticity, on the other hand, was permanently lowered due to ASR, notwithstanding the variable rate of reduction. Several researches have said, and nearly all of them agreed, that the modulus of elasticity is quite sensitive to ASR and can easily be lowered and influenced by ASR. [51,52]. Swamy and Al-Asali [44] discovered 60-80% modulus of elasticity losses in concrete specimens with free expansion containing highly reactive aggregates.

Gautam [46] studied the effect of multiaxial stress on the expansion and mechanical property degradation of ASR-affected concrete. The authors created reactive aggregate concrete cubes and exposed them to uniaxial and biaxial shocks. Cured cubes were tested for mechanical characteristics degradation in an acceleration chamber maintained at 50 °C and 100% relative humidity. The author reported average decreases of 20% in the modulus of elasticity of the concrete in the test specimens.

The existence of micro cracks caused by ISR expansion, either by AAR or DEF, has a considerable impact on the modulus of elasticity of ISR-affected concrete and can be reduced dramatically even at low expansion levels [53-55]. The impacts of ASR on structure are shown in the tables below by Sanchez et al [53] as a drop in compressive, tensile, and modulus of elasticity.

Given the pace of expansion, the decline can vary. For low or average expansion (0.05%), the compressive strength remains stable with less than 5% loss, the modulus of elasticity is lowered by up to 30%, and the tensile strength is reduced by 30% to 60%. Compressive strength loss is decreased by 25% for medium expansion (0.20%), modulus of elasticity is reduced by 35%, and tensile strength ranges from 50% to 60%. Compressive strength is reduced by 35% for significant expansion (0,30%), modulus of elasticity is lowered by 50%, and tensile strength remains stable at 60% loss.

All of these changes in concrete's mechanical characteristics have ramifications for the service limit states of concrete buildings, jeopardizing their quality and durability. When examining the structural implications of ISR damage, keep in mind that the relationship between compressive strength, tensile strength, and modulus of elasticity is not always the same as it is for sound concrete [54]. Compressive strength is typically the least affected mechanical attribute of ISR damaged concrete (particularly for AAR) and should not be regarded as a main predictor of structural reaction. Concrete structure performance at the serviceability limit states is more sensitive to changes in tensile strength and modulus of elasticity, which affect cracking, deflections, bond strength, and other properties [56].

The presence of internal reinforcement, geometric discontinuities, stress levels, and pre-existing cracks can all influence the orientation of the earliest visible evidence of ISR deterioration.

Because of structural loads, shrinkage, temperature fluctuations, foundation settlement, or other processes, reinforced concrete is frequently cracked in service even before ISR develops. A thorough diagnostic examination should be performed to discover the true cause(s) of cracking [57]. Cracking, on the other hand, might be a good predictor of the progression of degradation and growth [53].

Chapter 3

3. Experimental Program

3.1 General Organization

A total of two hundred and forty standardized cylindrical structural concrete specimens measuring 20 cm in height and 10 cm in diameter were made at the Structures Laboratory of the Catholic University of Pernambuco. Of this number of specimens produced, 120 were separated for the diametrical compressive strength, axial tensile strength and axial compressive strength tests under normal conditions, i.e. without any internal expansive reactions. The remaining part was subjected to an environment with conditions to accelerate the process of installation and evolution of internal expansion reactions, the details of which will be presented and discussed below. The two batches of 120 concrete specimens were produced with different types of cement - 60 made with CP-IV cement and 60 with CP-V cement.

In summary, a total of 240 specimens were made, all using the same types of coarse and fine aggregate. Of these 240 specimens, 120 were made with CP IV-32 cement and 120 with CP V-ARI cement, both from the same manufacturer (Lafarge). The specimens were produced to be subjected to different curing conditions, where half of these samples would have their curing condition simulated to the conditions conducive to the appearance of AAR and the other half would be subjected to normal curing conditions, as elucidated in the flowcharts below. The Figure 5 and Figure 6 below illustrates the process described. The 120 concrete samples were used as reference samples for the mechanical tests performed.

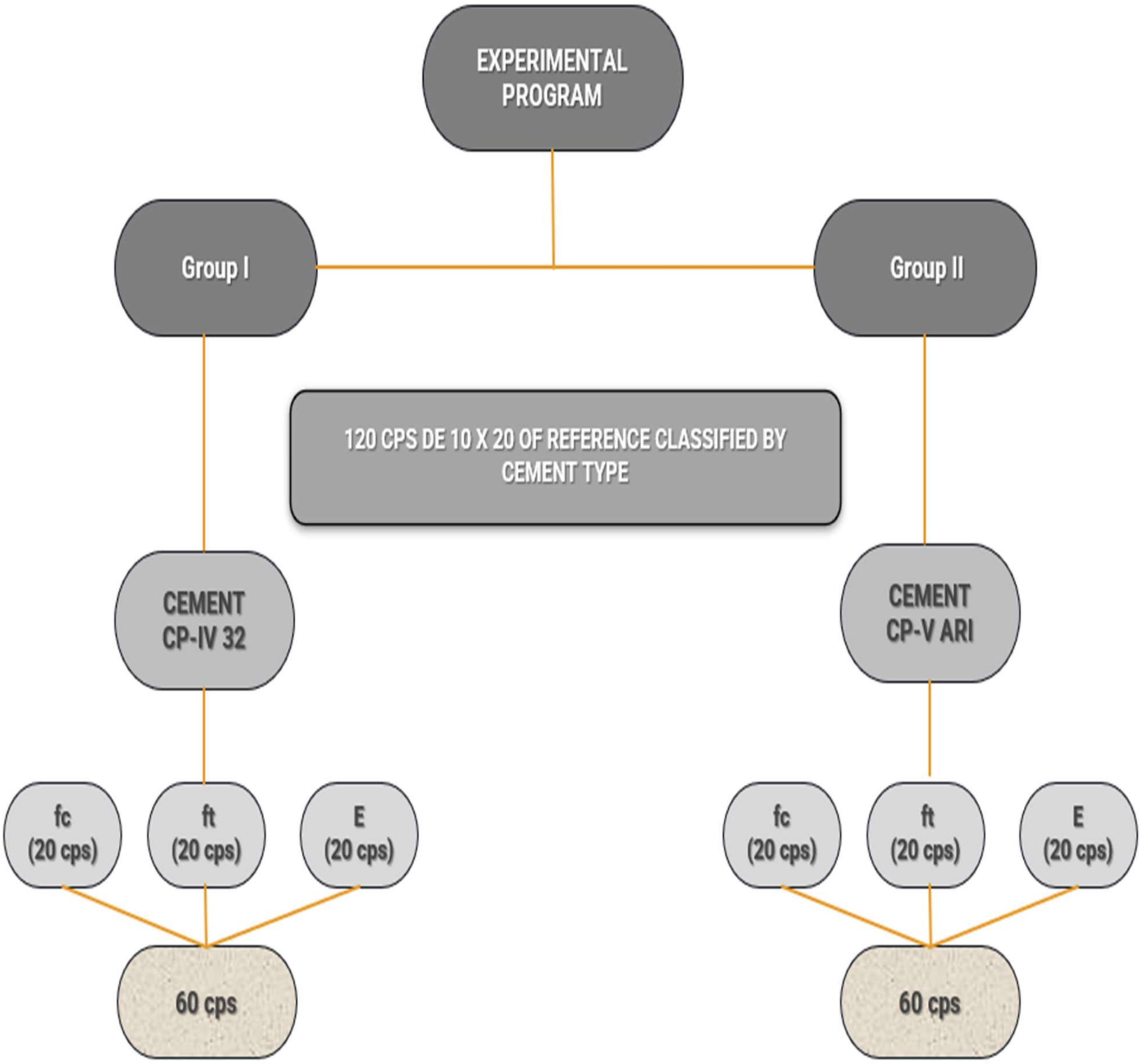


Figure 5 - Research methodology for making the reference specimens.

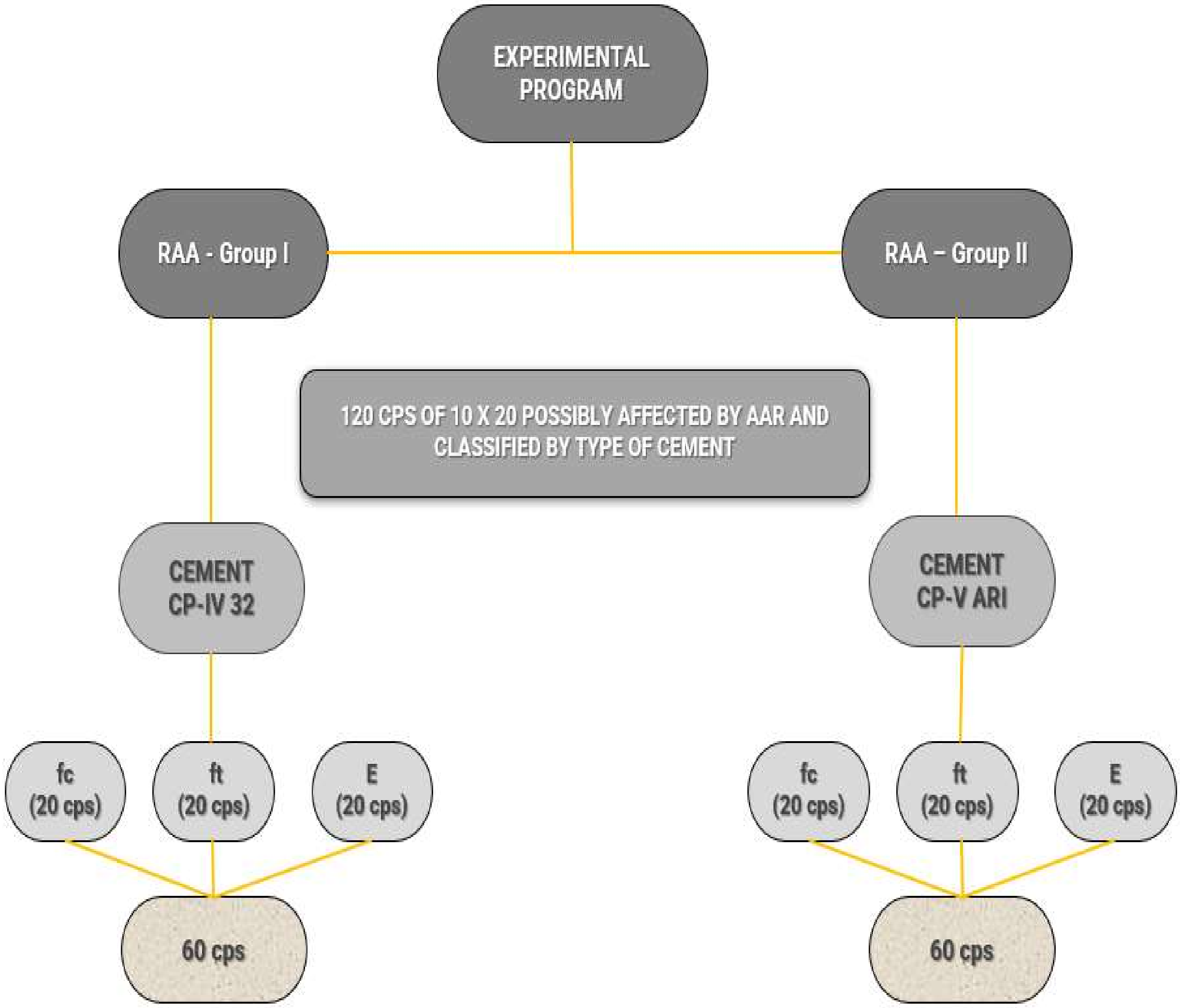


Figure 6 - Research methodology for making the specimens possibly affected by Alkali Aggregate Reaction.

The entire construction process, the simulation of the expansion reactions and the details of the experimental program will be presented and detailed below.

3.2 Preparation of the Concrete Specimens

The concrete used to make the specimens was made from materials available in the region and frequently used in reinforced concrete works.

3.2.1 Fine Aggregates

The fine aggregate used to make the cement was natural, coarse, innocuous, bagged sand, which is widely sold in the region. For the physical characterization of the aggregate, particle size, determination of fine materials, and clay and clod content tests were carried out. The following results were obtained from these tests:

- Maximum characteristic size = 4.75mm;
- Determination of fine material passing through the 75µm sieve by washing = 2.04%;
- Determination of clay content in clods and friable materials = 0.57%;
- Fineness Module = 2.74;
- Pulverulent Material = 1.41.

To assess the reactivity of the fine aggregate, an accelerated test was carried out on mortar bars. To perform this test, it was necessary to prepare the aggregates properly. These must comply with the grain size required by the Brazilian standard, as shown in Table 1.

Table 1 – Required grain size of test material. (Source: ABNT NBR 15577-4:2018)

Sieve with mesh opening (ABNT NBR NM ISO 3310-1)		Mass quantity of material	
Passing	Retained	%	g
4.75 mm	2.36 mm	10	99.0
2.36 mm	1.18 mm	25	247.5
1.18 mm	600 µm	25	247.5
600 µm	300 µm	25	247.5
300 µm	150 µm	15	148.5

The accelerated test on mortar bars was carried out following the recommendations of standard NBR 15577-4:2018. The test consisted of molding 3 mortar bars with a water-cement ratio of 0.47 by mass, 440 grams of cement and 990 grams of aggregate. mass, 440 grams of cement and 990 grams of aggregate. The specimens were casted using prismatic molds with dimensions of 25 x 25 x 285 mm^3, as recommended by Brazilians codes. The results obtained indicated that the fine aggregate used did not show any reactive potential and could therefore be considered innocuous for internal expansion reactions.

3.2.2 Coarse Aggregates

The coarse aggregate used comes from a quarry located on the BR-232 highway, in the municipality of Vitória de Santo Antão - PE, a region located in the Pernambuco East Shear Zone (ZCPE). For physical characterization, particle size and specific mass tests were carried out. From these tests the following results were obtained.

- Maximum characteristic size = 19.00 mm;
- Unit mass in the dry compacted state = 1.379 kg/liter.

To perform the experimental program, petrographic analysis was carried out on coarse aggregates. The analysis was based on part 3 of the NBR 15777: 2018 code. The microscope used was an Olympus BX40. The material used for analysis was collected from two mining sites. Two fragments of fresh crushed rock were collected. The fragments measured 19 x 17 x 9 cm^3 and 21 x 8 x 7 cm^3. Thin slides were prepared from these fragments for observation under a petrographic microscope. Potentially reactive minerals were found at this stage of the experimental program.

For greater reliability in the research results, an accelerated test was also carried out on the coarse aggregate. The test was performed following all the recommendations of part 4 of the NBR 15577: 2018 code. To increase the alkali content of the concrete in the prism methods, sodium hydroxide in pearls was used in the concrete mixing water.

During the mesoscopic analysis of the rock used in this research the presence of light gray to white spots was observed, represented by prismatic and/or rounded feldspar phenocrysts. The phenocrysts, together with dark mica lamellae, are mostly aligned with the foliated aligned with the foliated structure of the rock. Figure 7 shows these aspects.

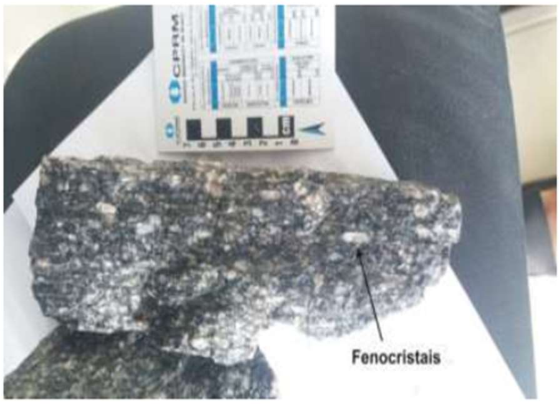


Figure 7 – General view of one of the rock fragments investigated.

Due to the location of the quarry (east Pernambuco shear zone), where the rock samples were taken, it was expected that the petrographic analysis would indicate that the coarse aggregate used exhibited any potential reactivity. Some aspects observed, like the formation of feldspar phenocrysts, indicate that there was an apparent rock recrystallization, suggesting a blastese process - growth of metamorphic minerals.

The photomicrograph at 2.5x magnification is shown in Figure 8. Some of the feldspar crystals in this image have been transformed into clay minerals indicated as altered feldspar phenocrysts) and the fillets, which are responsible for the foliation, are green to brown mica.

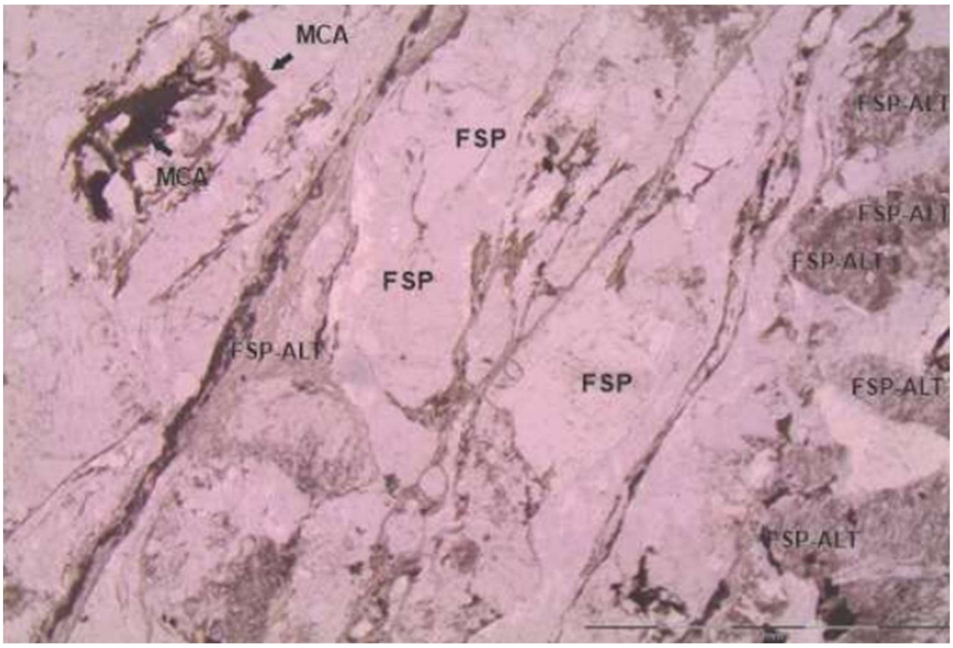


Figure 8 – General aspect of the rock seen under 2.5X magnification.
FSP = Fresh, unaltered feldspar phenocrystals; FSP - ALT = Altered feldspar phenocrystals; MCA = Micas

Recrystallized quartz (in granulometry millimeters) can be seen in specific locations on the image, showing undulating extinction and directed at an angle to the chlorite fillets, developing a chlorite, creating a band within the rock that has undergone intense recrystallization, made up of feldspar porphyroclasts surrounded by comminuted quartz and chlorite, as shown in Figure 9.

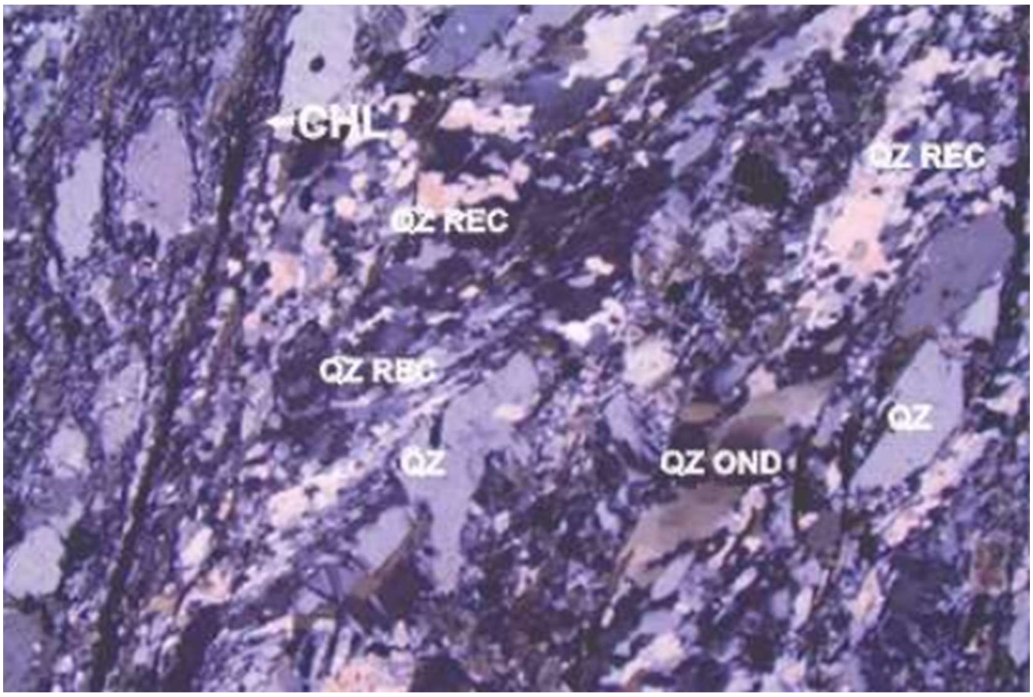


Figure 9 – Thin section under 2.5X magnification
QZ REC = Recrystallized quartz; CHL = Chlorite fillets; QZ OND = Millimetric grains of quartz exhibiting undulating extinction

Myrmecite intergrowths were also found, as well as K-feldspar crystals with perthitic intergrowths of the "strings" and "flame" varieties. Figure 10 shows "flame" types, which have characteristics that favor the potential of alkali-aggregate reaction.

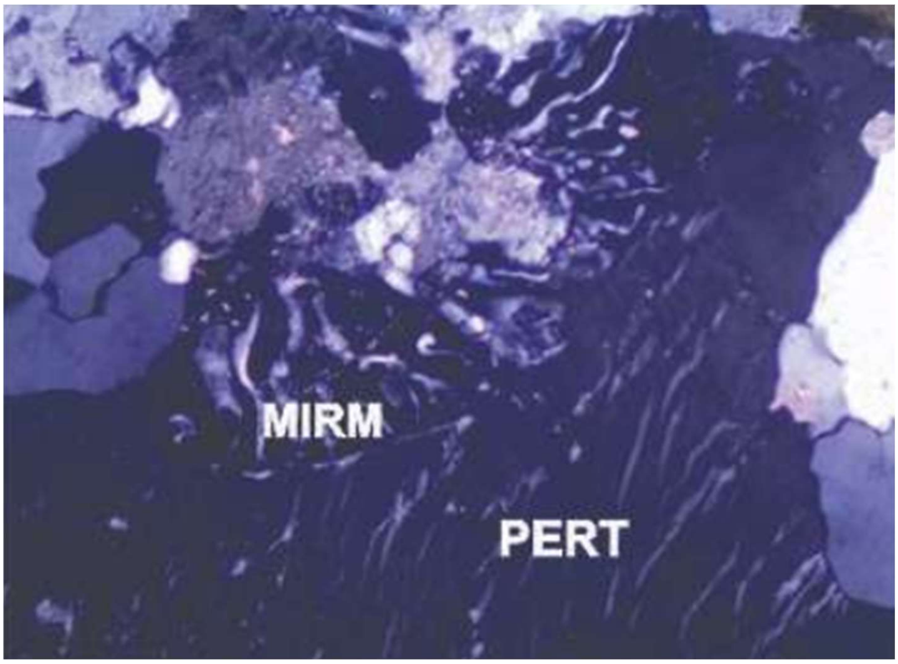


Figure 10 – Detail of a Feldspar crystal under 10 X magnification.
Pert = Perthitic intergrowths in the style of strings; Mirm = Myrmequite fans between feldspar and quartz

The characteristics presented indicate that the rock under consideration has undergone plastic-structural deformation, with obvious signs of recrystallization, both of the feldspars (especially the K-feldspars) and quartz, recrystallized in larger grains and showing undulating extinction. The percentage of comminuted, recrystallized quartz and myrmecite micro textures, together with the micas, accounts for approximately 50% of the rock's volume.

The remaining volume of the rock consists of phenocrysts, some showing recrystallization in oval shapes, while others show ambiguous shapes with clearly fractured edges. Approximately 50% of the rock's volume comprises fractured material located between the resistant, unground mineral grains. Consequently, the rock under study can be categorized as a protocataclasite. According to NBR 15577-3:2018, the aggregate is classified as potentially reactive because it includes microcrystalline quartz, deformed macro granular quartz (undulating extinction). In addition, there are microcrystalline quartz aggregates in contact with larger grains, exhibiting a mortar texture.

3.2.3 Cements

The investigation included two types of cement: CP-IV and CP-V. This approach was adopted for two reasons: first, because these are two types of cement that are often used in concrete construction in the region, and second, because it was intended to investigate the effect of cement on the concrete deterioration process when affected by internal expansion reactions. CP-IV cement has a higher concentration of pozzolanic additions, whether natural or industrial by-products such as fly ash, granulated blast furnace slag, active silica, among others. The addition of pozzolanic materials has advantages for concrete, such as refining the pores, improving mechanical strengths such as compressive strength and increasing the cohesion of the cement paste, as it fills the voids that would otherwise be occupied by water.

Table 2 below summarizes the properties of the cements used throughout the research.

Table 2 – Chemical properties of cement.

The chemical composition of cement	Values (%)	
	CP IV	CP V
Calcium oxyde (CaO)	39.5	65.6
Silicon dioxide (SiO_2)	29.8	15.0
Aluminum oxide (Al_2O_3)	11.5	3.3
Magnesium oxide (MgO)	4.1	4.6
Iron Oxyde (Fe_2O_3)	3.8	3.4
Sulphur trioxide (SO_3)	3.6	2.7
Potassium oxide (K_2O)	1.5	0.9
Titanium dioxide (TiO_2)	0.6	0.4
Sodium oxide (Na_2O)	0.5	0.2
Specific surface area (m^2/g)	12.2	6.4

3.2.4 Concrete Mixtures

The American Concrete Institute (ACI Committee 211 - [58]) method was used to define the concrete mix, the steps for which are summarized below.

The design compressive characteristic strength of the concrete was set at 35 MPa, a value that represents the practice of concrete construction in the region. The values of the variables of the ACI method used to make all concrete batches are listed below.

- Choice of slump range value = 10±20 mm;
- Choosing the maximum characteristic size of the aggregate = 19 mm;
- Estimation of mixing water consumption and air content = 224 kg/m^3 with 1% of air content;
- Definition of the water/cement factor = 0.45;
- Estimating cement consumption = 497 kg/m^3
- Estimating the consumption of coarse aggregate = 1,043 kg/m^3;
- Estimating the consumption of fine aggregate = 546 kg/m^3;

Table 3 below summarizes the information on the concrete mixes used to produce all the test specimens.

Table 3 – Concrete mixture proportion.

Concrete Mixture Proportions – 1.0 : 1.1 : 2.1 : 0.45		
CC = 497 kg/m³ f_{ck}: 35 MPa		
228 liters of water per solution		
Concrete Mixture Proportions	**CP IV**	**CP V**
Cement (kg/m³)	497	497
	(80)*	(80)
Sand (kg/m³)	546	546
	(88)	(88)
Coarse aggregate (kg/m³)	1,043	1,043
	(168)	(168)
Water (kg/m³)	224	224
	(36)	(36)

*The number in brackets are the weight occupied by the materials in the mixture.

3.2.5 Strategies for Creating a Favorable Environment for the Initiation and Spread of ASR

A tank made with material resistant to high temperature was used to store of all concrete specimens. In order to avoid contact between the specimens and the tank surfaces, a high density polyethylene plate with holes was installed to accommodate them.

A resistance and a thermostat were installed in the container to control and maintain a constant temperature of 60 ± 2°C 60. Figure 11 and 12 illustrates the described procedure.

To simulate the internal expansions due to the alkali-silica reaction in the concrete specimens produced, the following procedure was used:

- After being cast, the 120 concrete specimens (60 made with CP-IV and 60 made with CP-V) were exposed to a solution of NaOH (1 mol/L) at 80 degrees centigrade, immersed, for 30 days;

- After this period, the specimens were placed in a metal tank with a constant temperature of 60°C (this strategy was based on Item 4 of Brazilian NBR 15577-4) for a period of 242 days;
- In this tank, the specimens were submerged in a 40 g/liter sodium hydroxide solution;
- The alkaline equivalent of was equal to 1.25% of the mass. NaOH at 1N was dissolved in the mixing water. This alkaline addition is introduced due to the need to obtain higher alkaline contents, in order to accelerate the onset of accelerate the onset of expansion in concrete prisms.

Figure 11 – Concrete specimens into the stainless-steel tank.

The stainless steel tank used to create the environment necessary to deleveop ASR in the concrete specimens had the following features:

- Stainless steel tank 3/4 with two compartments;
- Plate thickness: 1 mm;
- Overall dimensions: 2.00 x 0.60 x 0.60 m^3;
- A Digital Controller with a 3/16 stainless steel tubular insulated and shielded (20w x 380v) resistor was installed to assure the temperature level desired (Figure 12).

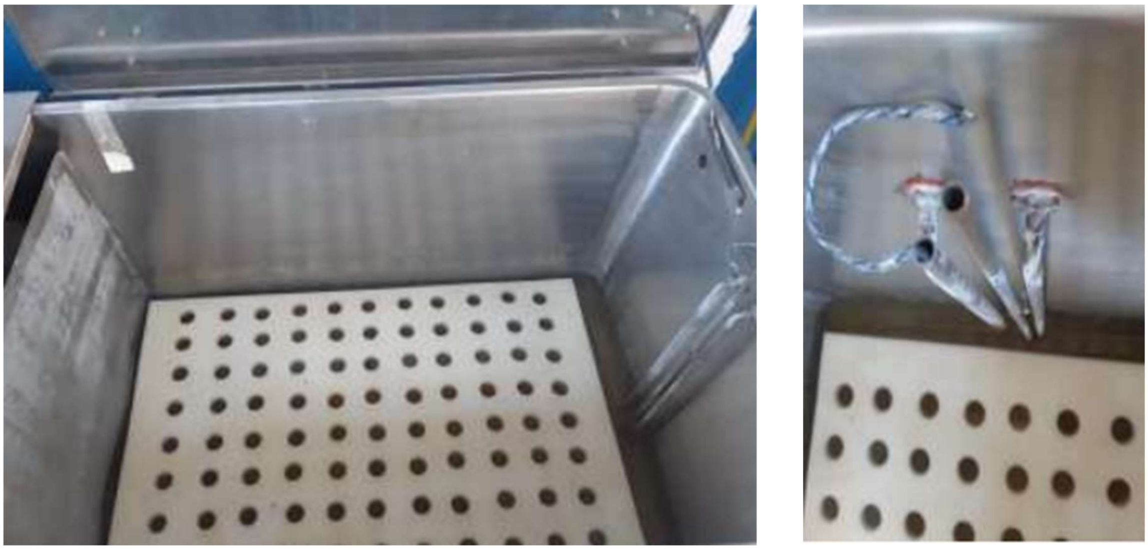


Figure 12 – Container for the test specimens and detail of the electrical resistance installation.

Below is a schematic presentation of the tank. A high-density polyethylene shield was placed at the bottom of the tank structure to prevent the specimens from coming into contact with the material in the tank.

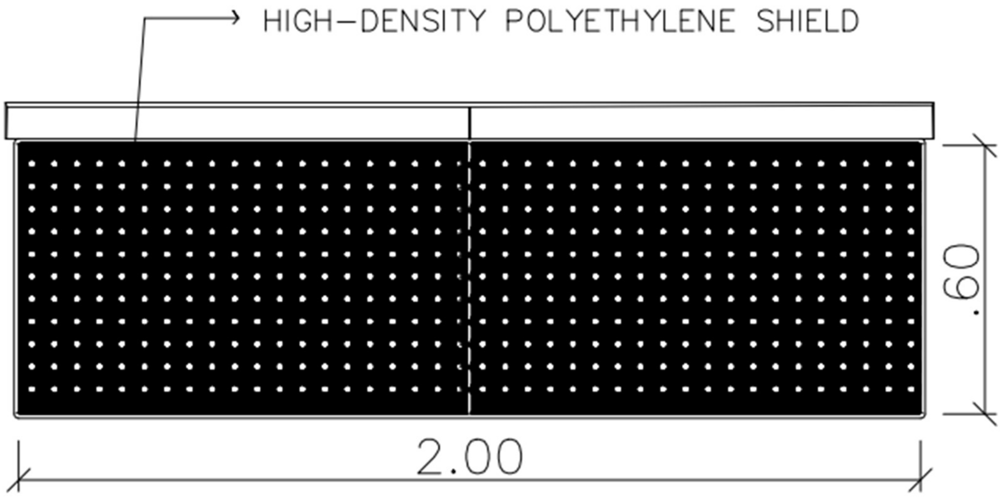


Figure 13 – Schematic plan of the tank.

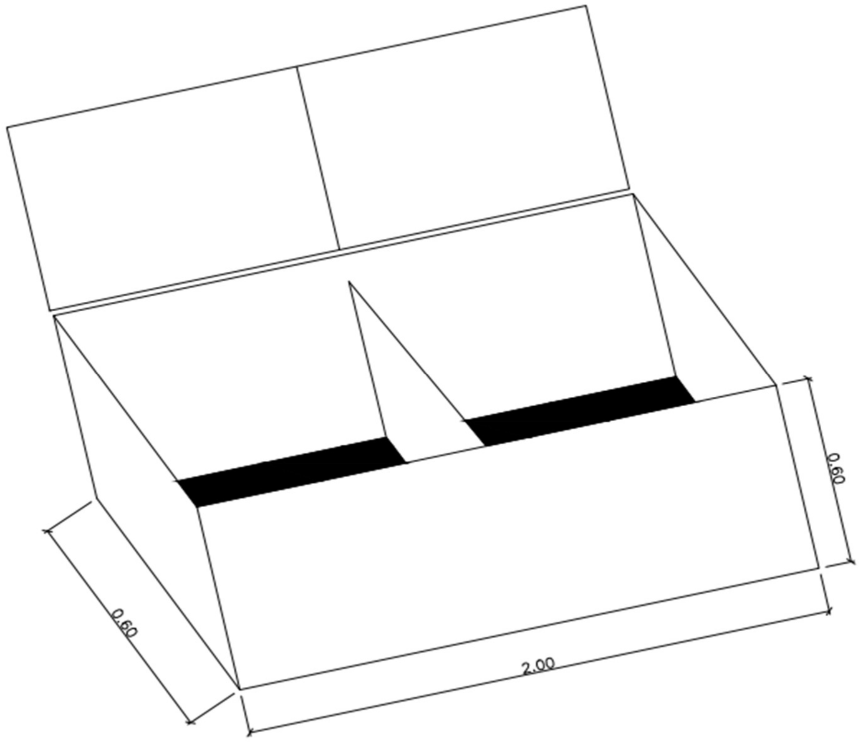


Figure 14 – Schematic drawing of the tank.

Regular checks on the level of the sodium hydroxide solution inside the tank and the temperature of the internal environment were carried out every two weeks. This was necessary to ensure that the initial conditions of the tests would not change over time.

After undergoing a 242-day curing process at 60ºC in a stainless steel tank, and following meticulous analysis of each specimen, it was determined that the ASR pathology impacted approximately 49 specimens made with CP IV and 51 specimens made with CP V. Out of the 120 specimens subjected to traditional curing (no ASR imposed condition), 62 were selected from the CP IV group and 64 from the CP V group. These selected specimens were used to perform mechanical test to be compared with those affected by ASR. Table 4 provides a comprehensive summary of both the quantity and distribution of specimens that were subjected to mechanical tests. The primary objective is to scrutinize the impact of Alkali-Silica Reaction (ASR) on the mechanical properties of concrete.

Table 4 – Number of concrete specimens chosen and separated for each type of test.

Status	Specimen attribute	ASR Affected specimens		ASR not affected specimens	
		CP IV	CP V	CP IV	CP V
		49	**51**	**62**	**64**
Initial planning	Available for testing	48	50	61	63
	Axial compression test	16	16	20	21
	Elasticity modulus test	16	16	20	21
	Split tensile test	16	16	20	21
	Remaining specimens =>	0	2	1	0
Executed	Axial compression test	16	16	18	1
	Elasticity modulus test	16	21	20	21
	Split tensile test	14	10	10	11
	Total number of tested specimens	46	47	48	46

Chapter 4

4. Analysis and Discussion

4.1 Accelerated Test on Mortar Bars Results

Mortar bar tests were performed for both fine and coarse aggregates as outlined in reference [59]. In this experimental procedure, mortar bars containing fine and coarse aggregates, along with a reference high alkali cement, were fully immersed in a 1 M NaOH solution at a temperature of 80 °C. Periodic measurements of the specimen's length were conducted, with the initial reading taken after 24 hours of immersion in the NaOH solution. Subsequent measurements were recorded at two-day intervals up to day 35, marking the conclusion of the accelerated mortar tests.

For each aggregate type, three mortar prismatic bars with a square cross-section measuring 25.0 ± 0.7 mm on each side and 285 mm in length (effective measurement length equal to 250.0 ± 2.5 mm) were meticulously prepared. The cement used was Ordinary Portland with a minimum Na2O equivalent (Na2O + 0.658 K2O) of 1%. Fine and coarse aggregates underwent processing through crushing and sieving to generate a graded sample in accordance with the specifications outlined in references [59] and [60].

Figure displays the outcomes of accelerated mortar bar tests for both fine and coarse aggregates. The results indicate that only the coarse aggregates exhibited a potential reactivity level of R1, implying expansions in the range of 0.19% to 0.4% at 30 days. In contrast, the fine aggregate showed no reactivity potential. Consequently, the sole source of reactivity stems from the planned use of coarse aggregates, aligning with the experimental campaign.

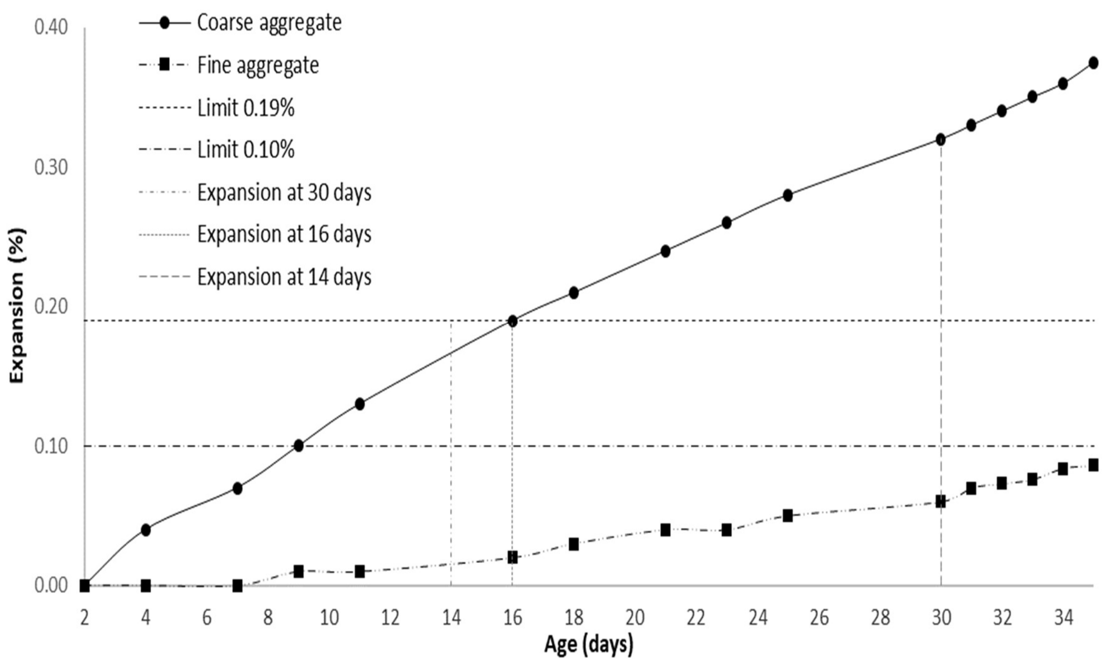


Figure 15 – Accelerated mortar bar test results – fine and coarse aggregates.

In

Figure 15 it can be seen that, at 16 days, an expansion limit of 0.19% was achieved, signifying that the coarse aggregates utilized can be categorized as rapid reactive aggregates. Notably, an expansion limit of approximately 0.10% at 14 days is sufficient to classify an aggregate as rapid reactive [61].

Therefore, it can be inferred that the coarse aggregate employed is indeed a very rapid reactive aggregate. Some codes permit the continuation of accelerated mortar bar tests up to 30 days when expansions at 14 days fall within the range of 0.10% to 0.20%, using a 0.19% expansion limit to designate an aggregate as reactive [59].

The mortar bars in the fine aggregate series exhibit a minor linear length variation of 0.02% and 0.06% at 14 and 28 days, respectively. This variation is deemed non-detrimental when utilized in concrete structures.

4.2 Visual Inspection of the Specimens

After the 243-day period planned for the process of initiation and development of expansive reactions due to ASR, the specimens were removed from the metal tank and then stored in the University's Structures and Materials Laboratory. A rigorous visual inspection was carried out on all one hundred and twenty specimens inside the metal tank.

Examination of concrete specimens yielded visual evidence of cracking and deposits of silica gel, indicative of the initiation of Alkali-Silica Reaction (ASR). The currently observed minimal cracking patterns imply a potential scenario of moderate reaction progression. Figure 16 shows some images of the visual inspection performed, where it can be seen signs of the ASR occurrence.

A superficial cracking process is more clearly visible in the fourth image in Figure 16. This process is the result of the C-S-H gel occupying the void spaces, generating tensile stresses which induce the micro cracks observed.

Figure 16 – Visual inspection – surface ASR effects on specimens

In order to observe the occurrence of C-S-H gel in the specimens in more detail, after the destructive tests to obtain the strength properties - tensile and compressive - of the concrete, additional visual inspections were carried out on some fractured specimens. Figure below shows images representing the situation observed.

Figure 17 – Visual inspection of fractured specimens

In this figure you can see the signs of the formation of the expansive gel due to ASR, a situation that ensures that the reaction has indeed taken place, as planned at the beginning of the research with the placement of the specimens in an environment capable of promoting the start and evolution of the reaction. The presence of cracks in concrete s a visible manifestation of the distress caused by ASR. These cracks typically exhibit a distinctive pattern, often resembling a map or random network, and are characterized by their location and distribution. ASR-induced cracks are more likely to appear in areas with higher concentrations of reactive silica aggregates. By identifying and analyzing these cracks, engineers and researchers can diagnose the presence of ASR in concrete structures. Monitoring and understanding these indicators are crucial for assessing the long-term durability and integrity of concrete elements, as uncontrolled ASR can lead to significant structural damage over time. Detection and mitigation strategies can then be implemented to address the effects of ASR and ensure the longevity of concrete structures.

A more detailed view of a part of the fractured specimen showing signs of expansive gel was obtained using a magnifying glass TRIPLET with 10x magnification and a lens diameter of 20.5 mm - Figure 18 - where the presence of the C-S-H gel can be seen more clearly.

Figure 18 – Crystals of the expansive gel can be seen through a magnifying glass.

The presence of crystals formed by the expansive gel in concrete can have significant effects on the structural integrity and durability of the material. Expansive gels, often associated with reactions such as Alkali-Silica Reaction (ASR) or delayed ettringite formation (DEF), contribute to the expansion of the concrete matrix. As these gels crystallize, they generate internal pressures within the concrete, leading to various detrimental effects [4,7,58].

Firstly, the growth of crystals exerts mechanical stress on the surrounding concrete matrix, resulting in the development of micro cracks and, over time, macro cracks. These cracks compromise the structural integrity of the concrete, potentially leading to reduced load-bearing capacity and increased susceptibility to other environmental factors. Secondly, the expansion caused by crystal formation may result in dimensional changes in the concrete. This can lead to deformations and displacement of structural elements, affecting the overall stability and functionality of the concrete structure [62-64]. Moreover, the presence of crystals may alter the permeability and durability of concrete. Cracks induced by expansive gel crystals provide pathways for the ingress of aggressive agents such as moisture and chemicals, accelerating the deterioration of the concrete over time. In order to mitigate the adverse effects of crystal formation, it is crucial to employ preventive measures and proper material selection during the concrete mix design process. This may include using low-alkali cements, incorporating supplementary cementitious materials, and carefully selecting aggregates with low reactivity.

4.3 Compression Tests Results

The results of the concrete specimens' compressive strength, affected or not affected by the internal expansion reactions due to ASR, were carried out in accordance with the applicable Brazilian standards - NBR 5738/2016 and 5739/2018 [65-66]. The first standard establishes the conditions for casting and the second establishes the procedures for carrying out compression tests on cylindrical specimens. Figure 19 shows the typical procedure for carrying out simple compression tests. The height/diameter ratio of the specimens was respected in all the tests carried out.

Figure 19 – Simple compression test scheme.

Simple compression tests on standardized specimens are widely used to assess the compressive strength of concrete due to their reliability, simplicity, and ability to provide valuable insights into the material's performance. These tests involve applying a compressive load to a cylindrical or cubical concrete specimen until failure occurs, allowing for the determination of the maximum load the specimen can withstand.

One key advantage of simple compression tests lies in their standardization. International standards, such as those established by ASTM, EN or Brazilian Codes, prescribe specific dimensions and testing procedures for concrete specimens. This standardization ensures consistency across testing methods, making results comparable and facilitating meaningful comparisons between different concrete mixes and batches. Standardized specimens also allow researchers and engineers to assess the influence of various factors on compressive strength under controlled conditions.

The simplicity of the compression test method is another factor contributing to its widespread use. The setup is relatively straightforward, requiring minimal equipment and procedures. This simplicity makes the test accessible to a broad range of laboratories and construction sites, enabling routine quality control assessments during concrete production. Additionally, the straightforward nature of the test facilitates quick and cost-effective evaluations, essential for large-scale construction projects where time and resources are crucial.

Furthermore, the compressive strength obtained from these tests is a fundamental parameter for evaluating concrete's structural performance. Compressive strength is a key indicator of a material's ability to withstand axial loads and support structural elements like columns and foundations. Engineers use this data to ensure that the designed concrete mix meets or exceeds the required strength specifications for a particular application.

During the development of the research, this test was chosen to assess the compressive strength of concrete specimens before and after the installation of internal expansion reactions due to ASR.

Figure below shows the rupture profile observed in the specimens subjected to the simple compression test, affected and unaffected by ASR - the third photo highlights internal micro-cracks with a red circle, compatible with typical manifestations of ASR. Failure modes observed are compatible with those reported by [4].

Figure 20 – Typical failure mode of compression test specimens.

Table 5 below summarizes the compressive strength results of all the specimens tested, affected and unaffected by ASR. This table also includes the dispersion measures for the samples in each group investigated, as well as the number of specimens tested in each condition. In addition, the table also shows the lower and upper limits of each sample, calculated using the interquartile range (IQR) concept. In this table, all the strength data are sorted in ascending order.

IQR is a powerful method for identifying outliers. The IQR (Interval Between Quartiles) method for detecting outliers was developed by John Tukey, the pioneer of exploratory data analysis. This was back in the days of manual calculation and graphing. At that time, the data sets involved were often small and the emphasis was on understanding the story the data told.

The interquartile range (IQR) is a measure of variation based on dividing a set of data into quartiles. Quartiles divide a data set sorted by rank into four equal parts. Q1, Q2 and Q3.

The IQR is defined as $Q_3 - Q_1$ and any data outside $\boldsymbol{Q_3+1.5 \times IQR}$ or $\boldsymbol{Q_1-1.5 \times IQR}$ is considered an *outlier*[2]. In all the samples investigated, only one outlier was observed, which is

[2] In statistics, an outlier, aberrant value or atypical value is an observation that deviates greatly from the others in the series, or is inconsistent. The existence of outliers typically affects the interpretation of the results of statistical tests applied to samples.

marked in red in Table 5. This value was excluded from the calculation of all the parameters of the respective sample because it possibly represents a value due to some inaccuracy that occurred during the tests and should therefore not be used in the analyses.

Table 5 – Simple compression test results – f_c (MPa).

Ref. #	ASR not Affected specimens		ASR affected specimens	
	CP IV	**CP V**	**CP IV**	**CP V**
1	45.43	42.18	37.31	41.42
2	46.98	48.40	37.55	47.67
3	47.53	53.65	37.61	49.16
4	48.48	54.40	37.62	49.34
5	48.48	54.42	39.46	49.48
6	49.12	54.67	39.87	50.46
7	49.20	55.38	39.97	50.49
8	49.55	56.07	40.64	50.96
9	49.85	56.33	41.20	51.30
10	50.15	56.43	41.30	52.13
11	50.43	57.30	42.26	52.24
12	50.81	58.14	42.57	52.91
13	51.27	58.84	42.99	53.64
14	51.48	60.65	43.82	53.82
15	51.50	-	44.26	55.54
16	52.08	-	**60.09**	56.10
Dispersion measures				
Average	**49.82**	**54.78**	**40.56**	**51.04**
Range	**6.90**	**18.47**	**22.78**	**14.68**
IQR	**3,01**	**3.30**	**4.95**	**4.08**
SD	**1.92**	**4.61**	**2.35**	**3,46**
CV	**3.86%**	**8.42%**	**5.79%**	**6.79%**
$Outlier_{inf}$	**43.97**	**49.27**	**30.20**	**43.25**
$Outlier_{max}$	**55.99**	**62.46**	**50.31**	**59.58**
		% fc reduction	**-18.58%**	**-6.82%**

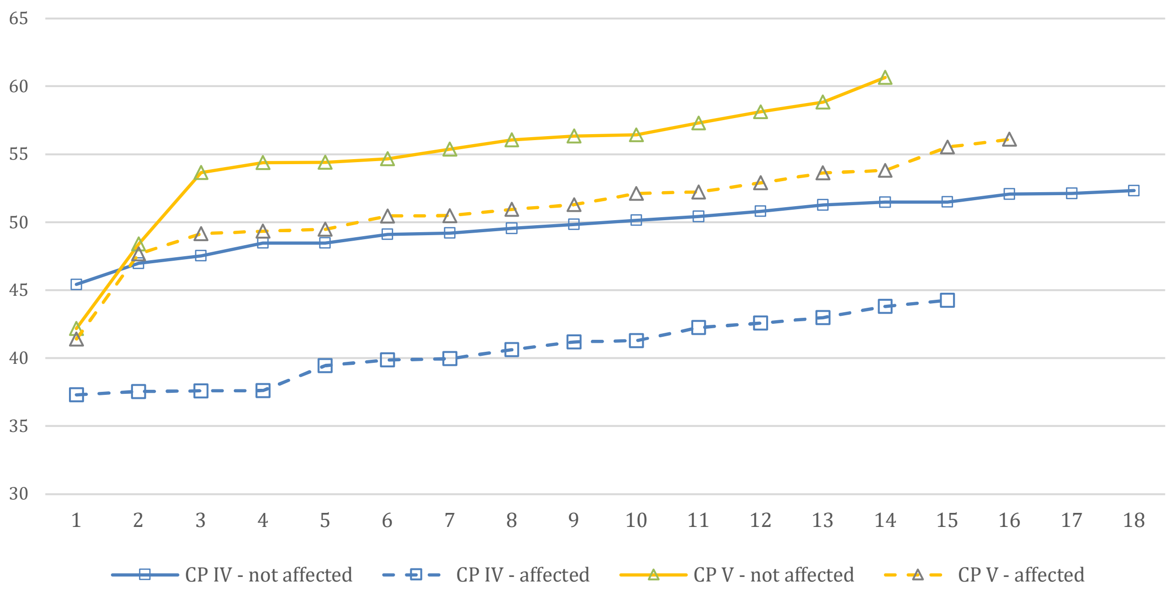


Figure 21 – Compressive strength of all specimens tested.

Table 4 shows that the coefficients of variation (CV = SD/Average) of all the groups studied - concrete made with CP IV and CP V, affected and unaffected by ASR - were within values considered acceptable of average or excellent control of fabrication, according to [67] reproduced in Table 6.

Table 6 – Degree of concrete control.

Type of concrete control	Coefficient of variation (%)
Poor control	> 14
Average control	= 10.5
Excellent control	< 7

In addition, by analyzing the dispersion measures in the table, especially the averages, it can be seen that the decrease in compressive strength of the specimens made with CP-IV cement after exposure to ASR was 18.58%, while those made with CP-V cement was 6.82%. This means that the specimens made with CP-IV cement were more affected by the effects of ASR on their ability to support compressive stresses - 2.7 times more than the specimens made with CP-V cement. This behavior is also visible in the curves shown in the graph in Figure 21, in which a greater separation can be seen in the curves of the specimens with CP-IV cement than those with CP-V cement.

This is an apparently inconsistent result because CP-V cement is richer in calcium oxide than CP-IV cement - 65.6% and 39.5, respectively (see Table 2). On the other hand, the alkaline oxides of the two types of cement investigated are also different (see Table 2), which leads to different alkaline equivalents - 1.487% and 0.792%, respectively for CP IV and CP V. This explains why the specimens made with CP-IV cement experienced a greater loss of compressive strength. Ongoing cement hydration that provided some positive effect on strength may be the another reason for the decrease in the loss rate in compressive strength observed in the test with the two types of cement used. In fact, since CP-V cement has a higher initial hydration rate than CP-IV at early ages and the opposite at ages greater than 28 days, the effects of internal expansion due to AST tend to be more pronounced in specimens made with CP-IV cement.

Other studies have investigated the influence of ASR on the compressive strength of concrete. [79] examined two highly reactive aggregates, one of which was fused silica, as well as a low reactive aggregate that served as a control. The cube specimens were cured in water at 20°C for 28 days before being heated to 38°C to speed up the hydration process. The strength decreased at both 20°C and 38°C as the expansion increased. At 38°C, however, a significant reduction was seen, particularly in the combination containing highly reactive fused silica.

The studies in [75-78] were carried out using materials of the same origin and quality as those investigated in this research, and some of them were carried out on cores extracted from concrete foundations affected by ASR, and the results reported are similar to those obtained.

Another study [80] found that compressive strength increased in a mix containing reactive fused silica and asserted that curing concrete with slowly reaction aggregate at high temperature has no increased effect on compressive strength of concrete at an early age or even after total time has passed. Similarly, [81] concluded that ASR expansion reduces compressive strength. However, several investigations have shown that ASR has no substantial effect on compressive strength [83, 84]. The causes for these inconsistent results might be attributed to specimen type, test settings, and material characteristics [82].

The observed reduction values are consistent with the studies by Sanchez et al. (2018) and Diab et al. (2020) - Figure 22 and Figure 23 - and can be compared to the results between 0.05% and 0.2% expansion, which show a 5% to 25% reduction in strength, according to Sanchez et al. (2014), and an 18% reduction for 0.2% expansion or 6 months of age, according to Diab et al. (2020). This shows that Nascimento's (2020) approach for inducing ASR in specimens produces this amount of concrete expansion. It was classified as having low to medium growth rates. Mohammad S. Islam et al. (2014) found that compressive strength was not susceptible to ASR at an early age, which corresponds to our concrete's minimal expansion.

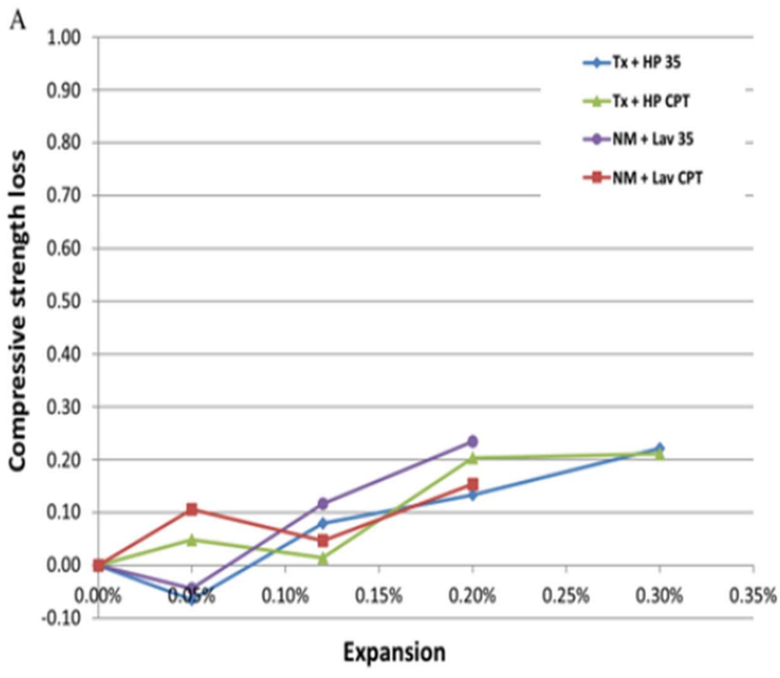


Figure 22 – Compressive strength reduction. Source: Sanchez, 2018.

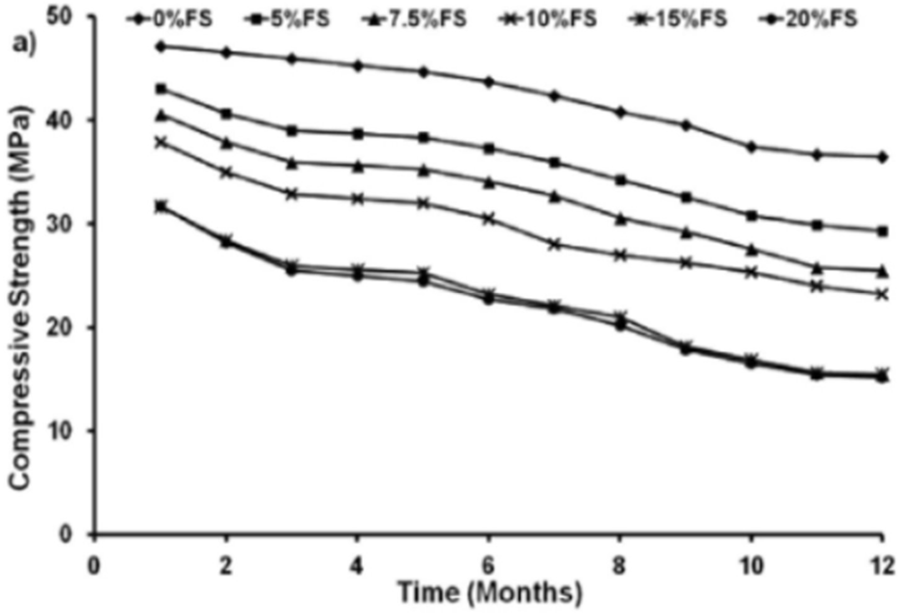


Figure 23 – Compressive strength reduction for 0% FS. Source: Diab, 2020.

This difference may be due to the nature of the aggregates used, as we know that they have a different impact on the reaction depending on the lithology, but mainly due to the property of CPV, which continues to significantly increase its compressive strength after 28 days, as it was observed in the investigation performed.

The primary goal of this research was to determine if concrete expansion is proportionate to the existence and incidence of RAS, as well as the implications for mechanical qualities. In reality, the affected material's compressive strength was not greatly reduced, confirming that, while compressive strength is impacted by ASR, it is not the best information for detecting the early existence of ASR. This is critical since compression tests are currently the industry's preferred test for determining the quality of concrete, which can lead to inaccuracies in ASR detection.

4.4 Tensile Test Results

The tensile strength of concrete falls between 8% and 15% of the compressive strength. The actual value is strongly affected by the type of test carried out to determine the tensile strength, the type of aggregate, the compressive strength of the concrete, and the presence of a compressive stress transverse to the tensile stress [69-71].

Two types of test are commonly used. The first is the modulus of rupture or bending test [72,73], which involves loading a simple, usually long concrete beam in bending at the third points of a 60 cm span until it ruptures due to cracks in the tension face. The flexural tensile strength, or modulus of rupture, of a modulus of rupture test is calculated using the following equation, assuming a linear distribution of stress and strain.

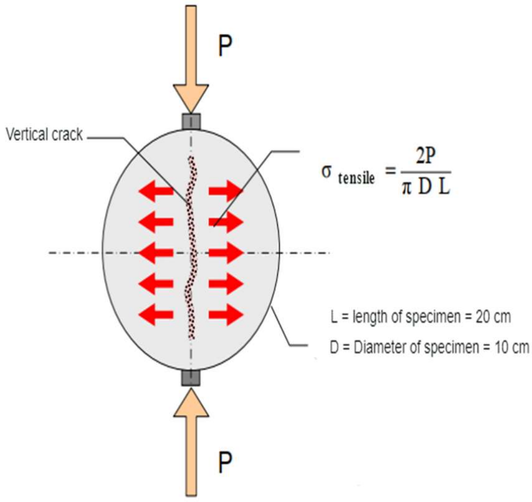
$$f_r = \frac{6M}{bh^2}$$

where:

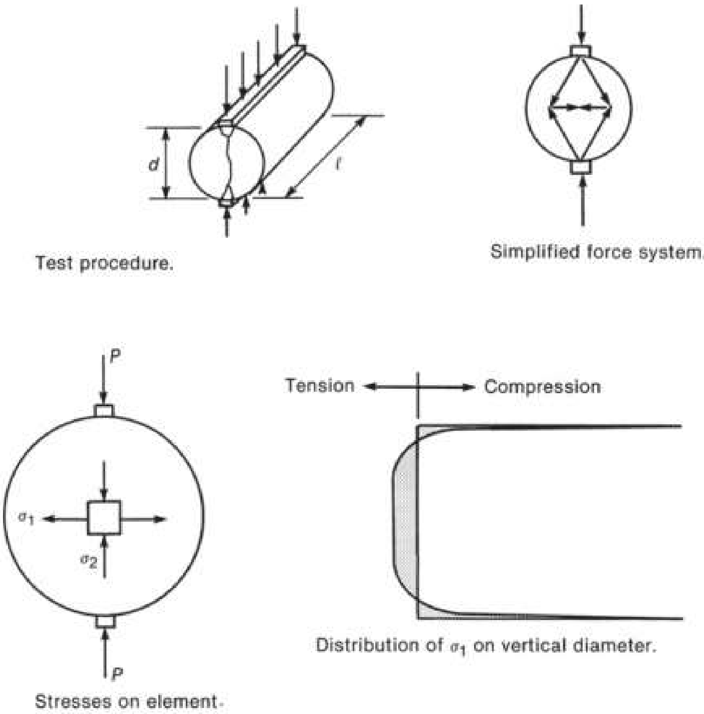
- M = bending moment due the applied loads;
- b = width of specimen and
- h = overall depth of specimen.

The second common tensile test is the Brazilian Test [68], in which a standard compression test cylinder - the same used for simple compression tests - is placed on its side and loaded in compression along a diameter, as shown in Figure 24.

(a) Schematic of tensile test



(b) Loads and stresses



(c)

Figure 24 – Schematic and characteristics of the Brazilian test.

The tensile stress created eventually divides the specimen into two parts along the vertical diameter and because of that the test is usually referred as split test.

Another type of tensile test is prescribed in some standards for the design and execution of concrete structures - the direct tensile test - but its difficulty in execution means that it is not widely used in the technical and research field.

According to researchers, among the three testing techniques (direct tensile, Brazilian test and bending test), the Brazilian test provides the best accurate determination of the real tensile strength of concrete-like materials over a wide strain rate [85]. For these reasons, the evaluation of the tensile strength of all the concrete specimens was carried out using the Brazilian test, which is regulated by the Brazilian standard NBR 7222/2011 [68].

[87-88] applied the gas pressure test approach to investigate the impact of AAR on tensile strength. Concrete test cylinders or cores are exposed to consistent pressure on their curved surfaces within a sealed cylindrical test chamber using compressed gas. The test cylinder is then subjected to a monotonic rise in gas pressure until it fails transversely to its axis of rotation. It is the consequence of a hydrostatic reaction in the pore water and a biaxial reaction in the solid phase, which culminate in a net internal tensile force created by the pore fluid [8]. Figure shows a schematic depiction of the suggested test. The cylinder's two flat ends are left exposed to the environment, resulting in a net induced tension field within the concrete sample parallel to the cylinder's longitudinal axis.

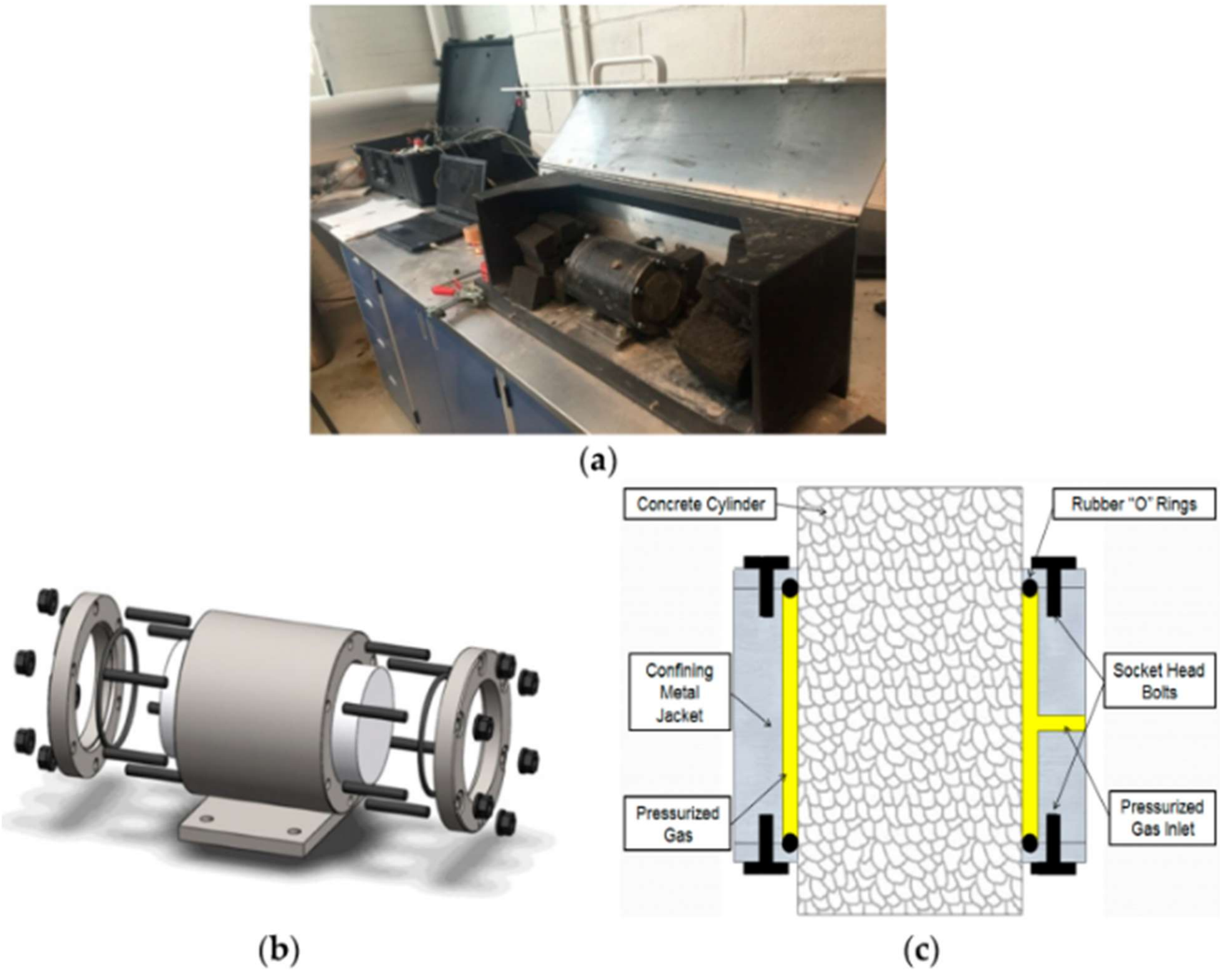


Figure 25 – Schematic representation of the concrete pressure tension test (from [89]).

The tests carried out in this research used the Brazilian method to assess the tensile strength of the specimens produced, because the equipment used to carry out the tensile test is still being manufactured at the University. Nevertheless, a comparison will be made between the tests carried out by the University and others available in the literature and with specific satellites.

Table 7 below summarizes the tensile strength results of all the specimens tested, affected and unaffected by ASR. This table also includes the dispersion measures for the samples in each group investigated, as well as the number of specimens tested in each condition.

Table 7 – Simple tension test results – f_f (MPa).

Ref. #	ASR not Affected specimens		ASR affected specimens	
	CP IV	**CP V**	**CP IV**	**CP V**
1	2.33	2.39	1.91	1.74
2	2.58	2.91	2.07	2.00
3	2.60	3.09	2.33	2.19
4	2.79	3.12	2.34	2.38
5	2.91	3.15	2.44	2.47
6	2.94	3.34	2.51	2.49
7	2.96	3.43	2.54	2.52
8	3.06	4.07	2.56	2.83
9	3.60	4.27	2.65	2.84
10	3.79	4.34	2.75	2.86
11	-	4.39	2.77	-
12	-	-	3.30	-
13	-	-	3.43	-
14	-	-	3.66	-
Dispersion measures				
Average	**2,96**	**3,50**	**2,66**	**2,43**
Range	**1,47**	**1,99**	**1,75**	**1,12**
IQR	**0,61**	**1,19**	**0,56**	**0,69**
SD	**0,45**	**0,67**	**0,50**	**0,37**
CV	**15,23%**	**19,10%**	**18,74%**	**15,31%**
Outlier_inf	**1,68**	**1,30**	**1,49**	**1,10**
Outlier_max	**4,11**	**6,06**	**3,74**	**3,87**

		% fc reduction	**-9.95%**	**-30.49%**

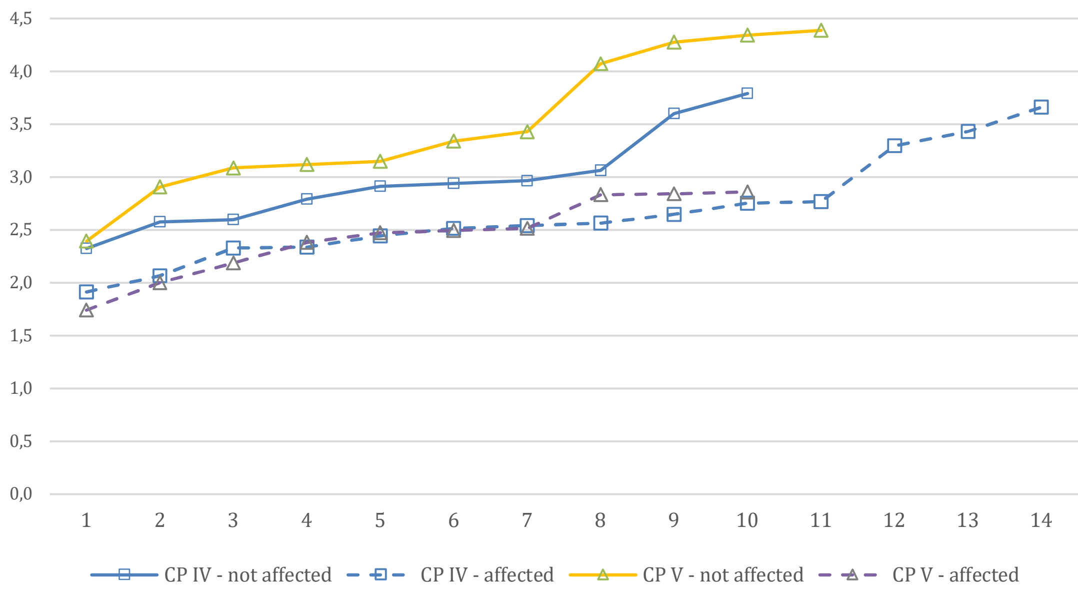


Figure 26 – Tensile strength of all specimens tested.

In addition, the table also shows the lower and upper limits of each sample, calculated using the interquartile range (IQR) concept. In this table, all the strength data are sorted in ascending order.

The first observation in Table 7 highlights a behavior that is quite different from what was seen in the data from the compressive strength tests - the coefficients of variation (CV) of the specimens tested in tension are much higher than those obtained in the compression tests.

In fact, in the tensile tests the CVs ranged from 15 to 19% while the CVs in the compression tests did not even reach 10% (the highest value was 8.42%). This behavior reflects the recognized difficulty of assessing the tensile strength of concrete, due to the intrinsically fragile nature of this material. Concrete has high compressive strength, but its tensile strength is significantly lower. In addition, the heterogeneous distribution of aggregates within the cement matrix contributes to the formation of micro cracks, which can adversely affect tensile strength.

In addition, the presence of factors such as humidity, variations in curing conditions and the quality of the materials used in the concrete mix can lead to significant variations in test results.

Looking at the data in Table 7, it can be seen that no tensile strength values are observed within the range Q_1***-1.5 x IQR*** and Q_3***+1.5 x IQR***, which means that there aren't any outlier in the sample and, this way, no value was taken out from the sample.

Furthermore, by investigating the dispersion measures in Table 7, particularly the averages values, one can observe that the compressive strength of specimens produced with CP-IV cement exhibited a decrease in tensile strength of 9.95% after exposure to ASR, whereas that of specimens made with CP-V cement decreased by 30.49%.

The reduction values of 9.95% for CPIV and 30.49% for CPV shown above do not agree with Sanchez et al. (2018), who showed a rapid and significant reduction in tensile strength in the early stage of ASR. However, the CPV results seem to be more in line with the study by Diab et al. (2020), with a 27% reduction after 6 months, corresponding to 0.2% expansion, and also with [77], that reported results in the range of 21 to 35%. On the other hand, [90] found that at expansions of 0.05%, 0.10%, 0.25%, and 0.50%, cylindrical specimens lose 15%, 25%, 45%, and 60% of their splitting tensile strength after 28 days, results that are convergent with those found in the research carried out.

Losses in tensile strength measured with gas pressure tests indicated significant reductions in variability - 12% to 50% - for low levels of expansion, values similar to those found in present investigation [91]. This fact highlights that the results with the Brazilian test produced similar results and, therefore, the test can be used to assess the tensile strength of concrete affected by ASR.

The results from the research developed indicate that the specimens made with CP-IV cement experienced a reduction in tensile strength 3.06 times greater than the specimens made with CP-IV cement. This situation is diametrically opposed to what was observed in the compression tests reported in the previous section, being the magnitude of the differences observed practically the same. This tendency is also obvious in the curves displayed in Figure 27, which demonstrate a higher divergence between the curves of specimens with CP-IV cement and those with CP-V cement.

The reasons for this apparent non-conformity between the behavior of the tensile test results and the behavior observed in the compression tests may, in the author's opinion, be related to the level of dispersion of the tensile test samples. In fact, the coefficient of variation of the specimens made with CP-IV cement was 19.10%, while those made with CP-V cement had a value of 15.31%, meaning that the tensile strength measurements of the specimens made with CP-IV cement were more variable.

Table 8 below shows the relationship between tensile and compressive strength for the specimens tested and the same relationship using the prescriptions of the Brazilian standard for the design and execution of concrete structures - NBR 6118/2023 - which allows the following equations to be used to estimate them.

- For concretes with $f_{ck} \leq 50$ MPa
  - $f_{ct,m} = 0.3\ f_{ck}^{2/3}$
- For concretes with $f_{ck} > 50$ MPa
  - $f_{ct,m} = 2.12 \times \ln [1+0.1\ (f_{ck}+8)]$

Table 8 – Ratio between f_t/f_c

Reference	ASR not Affected specimens		ASR affected specimens	
	CP IV	CP V	CP IV	CP V
Tests	5.93%	6.39%	6.56%	4.77%
NBR-6118/2023	8.15%	7.68%	8.73%	8.03%
Difference	-27.24%	-16.84%	-24.85%	-40.62%

An examination of the data in Table 8 shows that all the f_t/f_c ratios obtained in the experimental tests were lower than those resulting from the use of the strength correlation expressions provided for in NBR 6118-2023, for both unaffected and affected specimens due to ASR. This aspect highlights the inapplicability of relating tensile strength to compressive strength in ASR-affected specimens because the differences can be significant. The best strategy is to carry out specific tests to obtain the tensile strength of ASR-affected concrete.

A perdas de resistência máximas observadas à tração e à compressão foram de 30.49% e 18.58%, respectivamente. Isso significa que a perda de resistência à tração foi 64.05% maior do que a perda de resistência à compressão. Este resulto é consistente com pesquisas anteriores onde se reporta diferenças de 57.50% [78].

4.5 Modulus of Elasticity Test Results

In general, the modulus of elasticity, or Young's modulus, is the coefficient of proportionality between stress and strain during the elastic regime of the material.

However, the stress-strain curve of concrete is non-linear and the angular coefficient varies with the stress and the fit of the curve, for example, the modulus can be initial tangent strain (E_{ci}) or secant strain (E_{cs}). The name also depends on the stress regime, which can be static or dynamic.

Figure 27 shows typical stress-strain curves for concrete and its main components. Although the aggregate and matrix show linear behavior, the concrete shows non-linear behavior due to the presence of cracks at the interface between the matrix and the aggregates.

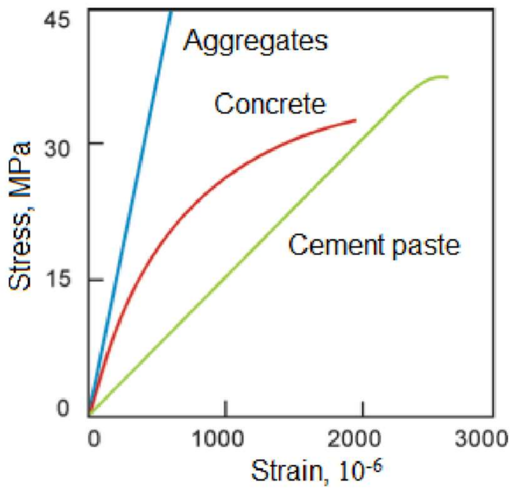


Figure 27 – Typical behavior of the stress-strain curve for concrete and its main components [4].

In general, the elastic modulus of concrete ranges between 30 and 50 GPa. Concrete with higher modulus of elasticity can support more stress before becoming brittle. In recent years, design requirements have required concrete to have a minimum value for the modulus of elasticity. Determining the modulus of elasticity is essential for calculating the stresses due to strains, as well as design stresses under load in simple and complex concrete elements.

Previous investigations have already demonstrated that the dynamic modulus of elasticity is not a valid measurement for diagnosing ASR. This conclusion stems from extensive research carried out by the authors using two types of sensitive to slow aggregate alkali reaction and two types of cements. Specimens were kept in a fog chamber for 560 days. Compressive strength, static and dynamic modulus of elasticity were evaluated at predetermined intervals. The static Young's modulus can be employed to predict the degree of damage and the rate of deterioration. Such predictions are not possible when determining the dynamic Young's modulus using the resonance frequency approach [92]. In view of these observations, the modulus of elasticity of the test specimens was determined using static tests in accordance with ABNT NBR 8522-1 [93] with the initial tangent modulus being taken into account in this assessment.

Modulus of elasticity of concrete is defined as the ratio of stress applied on the concrete to the respective strain caused. The accurate value of modulus of elasticity of concrete can be determined by conducting a compression test on a cylindrical concrete specimen attached with a strain-measuring equipment or compressometer as it shown in Figure 28.

Figure 28 – Concrete specimen in modulus of elasticity test.

To perform static calculation of the modulus of elasticity, preload cycles are recommended to accommodate the specimen in the testing machine before recording values (Figure).

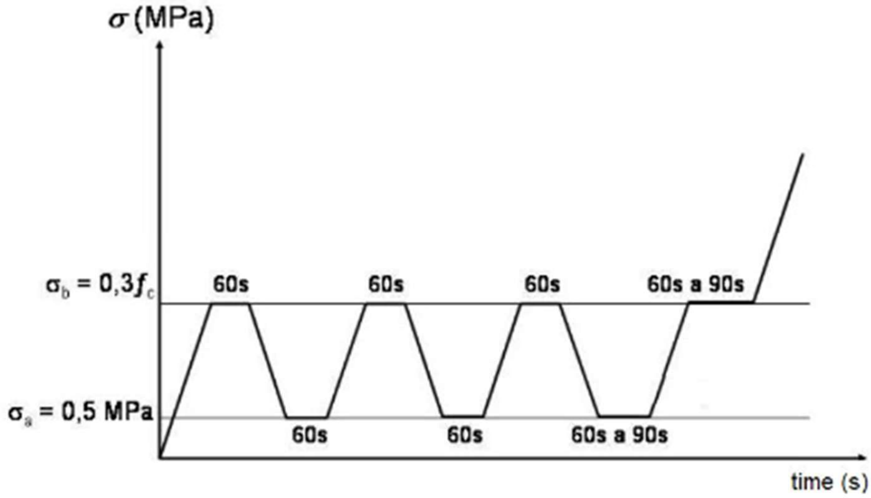


Figure 29 – Pre-loading procedure by ABNT NBR 8522-1 [93].

O valor do módulo de elasticidade foi determinado considerando a metodologia de tensão fixa que foi calculado conforme a equação seguinte.

$$E_{ci} = \frac{\Delta\sigma}{\Delta\varepsilon} 10^{-3} = \frac{\sigma_b - 0.5}{\varepsilon_b - \varepsilon_a}$$

where:

σ_b = Highest stress corresponding to 30% of compressive strength (σ_b = 0,3fc);

0,5 is the basic stress, expressed in MPa;

ε_b: Average specific strain of the specimens under the greatest stress;

ε_a: Average specific strain of the specimens under basic stress;

Table 9 below summarizes the modulus of elasticity test results of all the specimens tested, affected and unaffected by ASR. This table also includes the dispersion measures for the samples in each group investigated, as well as the number of specimens tested in each condition.

In addition, the table also shows the lower and upper limits of each sample, calculated using the interquartile range (IQR) concept. In this table, all the modulus of elasticity data are sorted in ascending order.

Table 9 – Modulus of elasticity test results.

Ref. #	ASR not Affected specimens		ASR affected specimens	
	CP IV - not affected	**CP V - not affected**	**CP IV - affected**	**CP V - affected**
1	25,561.89	32,092.84	15,089.36	19,059.71
2	25,861.35	33,479.32	16,420.49	20,106.38
3	26,207.02	34,046.20	16,652.28	20,239.35
4	26,826.43	34,155.01	17,743.85	20,517.03
5	27,169.76	35,067.24	18,026.55	20,615.64
6	28,726.66	35,667.17	18,097.21	21,959.44
7	29,569.19	37,013.79	20,323.23	22,310.93
8	30,070.86	37,302.37	20,355.74	22,356.80
9	30,201.29	37,583.99	20,486.86	22,538.54
10	30,637.78	37,592.44	20,834.67	23,618.74
11	30,757.48	38,268.19	20,904.74	23,811.64
12	30,863.72	38,382.42	21,854.69	24,122.81
13	32,260.27	38,850.57	21,935.07	24,284.05
14	32,393.77	39,713.48	22,159.19	24,330.27
15	32,695.16	40,311.60	22,392.25	24,481.59
16	33,845.07	40,830.86	23,083.12	24,512.38
17	34,289.69	41,066.63	-	25,954.05
18	34,449.95	41,857.95	-	26,837.89
19	34,988.07	43,907.99	-	26,892.09
20	35,921.09	45,056.98	-	28,014.46
21	-	46,231.11	-	29,136.91
Dispersion measures				
Average	**30,664.83**	**38,498.96**	**19,772,46**	**23,604.80**
Range	**10,359.20**	**14,138.27**	**7,993,76**	**10,077.20**
IQR	**5,998.61**	**5,581.54**	**4,100,45**	**3,945.68**
SD	**3,204.14**	**3,810.12**	**2,435,43**	**2,733.93**
CV	**10,45%**	**9,90%**	**12,32%**	**11,58%**
Outlier_inf	**18,561.07**	**26,994.90**	**11,663,85**	**15,369.03**
Outlier_max	**42,555.50**	**49,321.06**	**28,065,65**	**31,151.73**
		% fc reduction	**-35.52%**	**-38.69%**

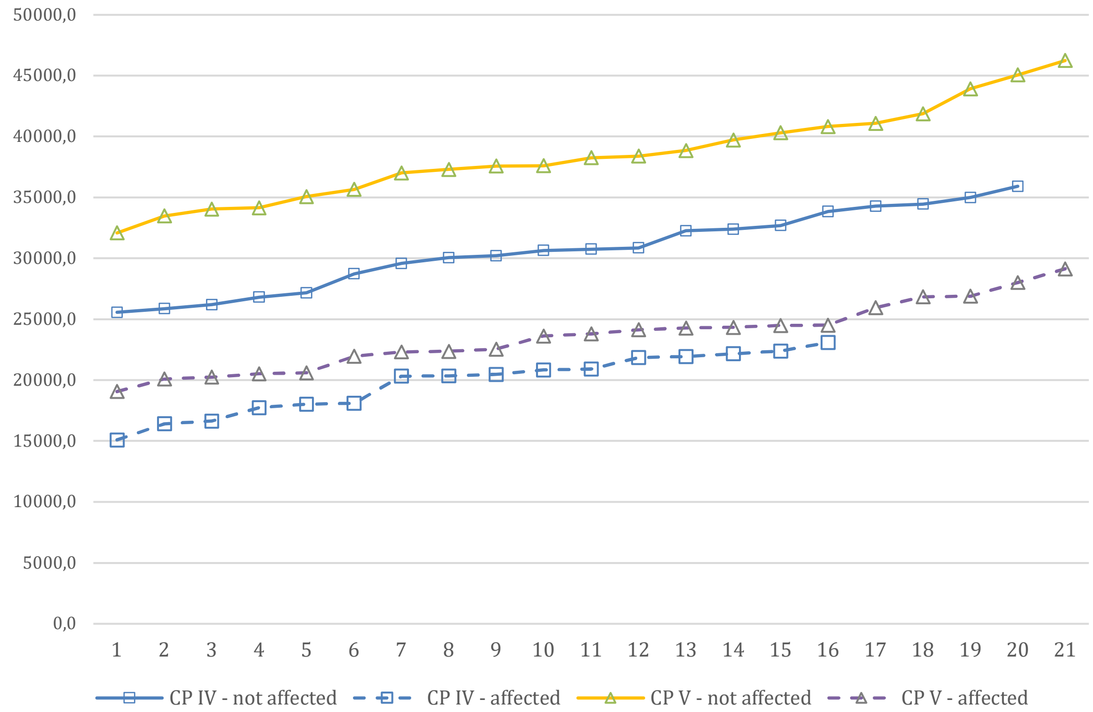


Figure 30 – Modulus of elasticity of all specimens tested.

Analyzing data in Table 9, it can be seen that no modulus of elasticity values are observed within the range $\boldsymbol{Q_1}$**-1.5 x IQR** and $\boldsymbol{Q_3}$**+1.5 x IQR**, which means that there aren't any outlier in the sample and, this way, no value was taken out from the sample.

The coefficients of variation of all the groups of specimens are very close to each other - the lowest was 9.90% and the highest was 12.32% -, an aspect that highlights the low variability of the sample data.

This result demonstrates the fact that the static modulus of elasticity of concrete is a very stable variable and, as reported by previous studies [92], it is a concrete property that has important applicability for predicting the degree of damage and the rate of deterioration of concrete elements affected by ASR.

The reductions in the static modulus of elasticity values for the specimens made with CP-IV and CP-IV cement were -35.52% and -38.76%. This reduction can be compared with the study by Sanchez et al. (2018) for 0.2% expansion and is almost 2 times lower than the results of Nascimento's thesis (2020) for expansion levels twice as high. Diab et al. (2020) also recorded a reduction of between 36% and 39% for similar expansion levels. This is in line with the compressive strength analysis of the degree of expansion. The results clearly show that the reaction has occurred and that this type of test is relevant to finding out whether ASR has occurred in concrete. It is a better tool for assessing damage and the presence of ASR than compression tests, as the results are more significant.

The values obtained in the static modulus of elasticity tests resulted in percentage reductions of the same order of magnitude, however, the specimens made with CP-V cement showed a slightly greater reduction in modulus of elasticity than those made with CP-IV cement. A probable explanation for the virtual difference observed (35.52% and -38.76%) may be related to the greater presence of cracks in the specimens made with CP-V cement, compared to those made with CP-IV cement.

In general, the results obtained for the static modulus of elasticity are consistent with previous research on the subject, as can be seen in Table 10 and Figure 31 below. Reductions in modulus of elasticity of up to 41.54% were observed over a 12-month test period.

The behavior exhibited in Figure 31 is very similar and the acceleration of the reduction seems to be the same for each cement.

This is a strong argument in favor of using the modulus of elasticity as a tool for detecting ASR, as it shows that the reaction affects both types of cement in the same way.

Figure 30 shows the results of the modulus of elasticity of all the test specimens, where the behavior described above can be seen.

Table 10 – Modulus of Elasticity and expansion with the time (Diab, 2020).

Time Month	MOE (GPa)	MOE (%)	Expansion (%)
1	26.14	0.00	0.023
2	23.97	-9.24	0.072
3	21.56	-18.36	0.104
4	19.93	-24.54	0.140
5	18.17	-31.20	0.164
6	16.66	-36.92	0.192
7	16.42	-37.83	-
8	16.21	-38.62	-
9	15.94	-39.64	0.218
10	15.70	-40.55	-
11	15.57	-41.05	-
12	15.44	-41.54	0.230

MOE = Modulus of Elasticity.

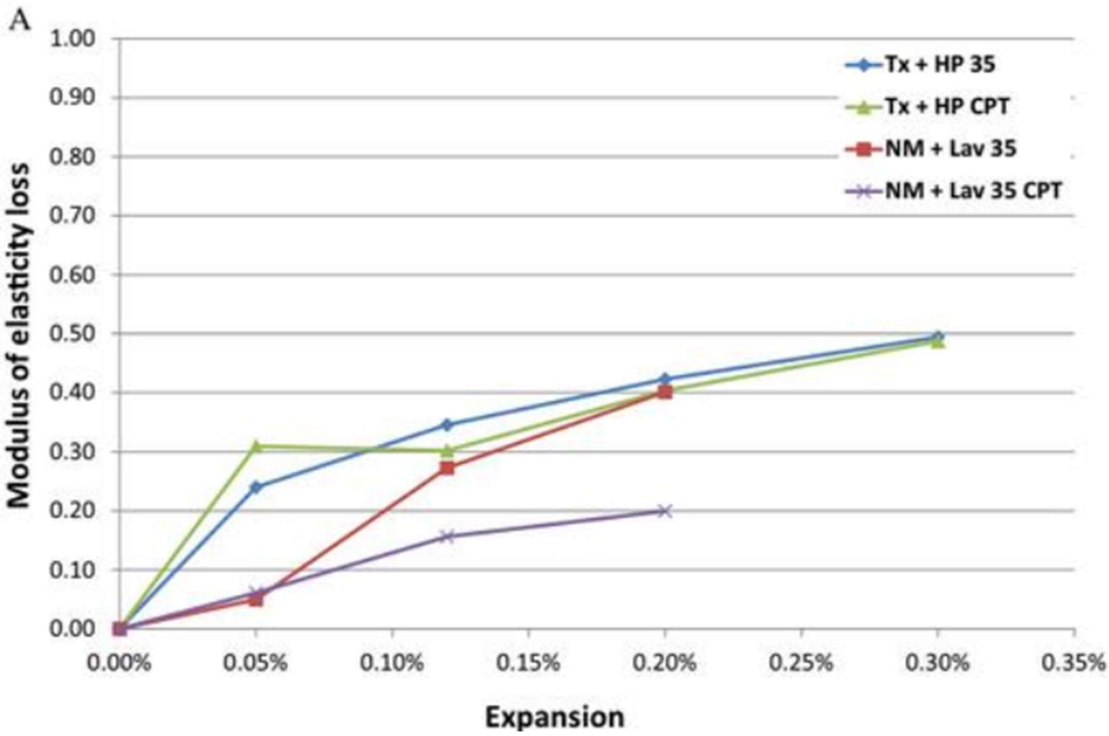


Figure 31 – Modulus of elasticity reduction (Sanchez, 2018).

Chapter 5

5. Conclusions and Recommendations for Future Works

This chapter will present the main considerations and conclusions obtained from the results and analyses carried out in the experimental program, being valid for the materials and conditions that they were submitted.

While significant progress has been made to understand the processes of AAR or DEF in concrete structures, much work remains to be done to predict the short and long-term performance of affected structures.

Assessing the structural consequences of ISR damage is critical for effective management and rehabilitation strategies. Comprehensive, multi-scale investigations and rational modelling methods combined with stochastic approaches are needed to develop useful prognostic models.

The presence of cracks and traces of expansive gel in the specimens confirmed the presence of the ASR reaction. This means that the methodology for stimulating ASR in concrete in the laboratory works. After the tests carried out, it can be seen that all three mechanical properties of the specimens (compressive strength, tensile strength and modulus of elasticity) stimulated by the alkaline silica reaction were affected and showed a reduction.

After carrying out the tests, it can be said that compressive strength tests are not effective in assessing the presence of ASR, since the decrease in compressive strength results observed is not so significant.

On the other hand, modulus of elasticity tests appear to be a reliable and appropriate methodology, as they show significant results, especially as the modulus of elasticity behaved similarly for CPIV and CPV.

The contribution of the results obtained in this study can be improved in the future by carrying out new tests for tensile strength, using the same methodology to make affected specimens. The correct application of the test methodology will need to be carried out to obtain more reliable results.

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