SAHC

ADVANCED MASTERS IN STRUCTURAL ANALYSIS OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

Master's Thesis

Bruno Favoretto Silva

Conservation of 20th Century Concrete Buildings - The Case of the Strahov Stadium in Prague

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

University of Minho

Czech Republic | 2019

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DECLARATION

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Supervisor(s): Cristiana Lara Nunes

Year: 2019

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

I hereby declare that the MSc Consortium responsible for the Advanced Masters in Structural Analysis of Monuments and Historical Constructions is allowed to store and make available electronically the present MSc Dissertation.

University: Czech Technical University in Prague

Date: 08/07/2019

Signature: ______________________________

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DEDICATION

It’s never easy to devote years of your life in projects and researches. It requires time, planning and dedication, especially if you‘re studying in another language and in another country. In this scenario outside the comfort zone, your family and your friends are always the ones who keep you focused on your goals.

Therefore, my sincere Thank You to all my family – especially my parents João Pereira da Silva Junior and Marília Carneiro Favoretto, and my siblings Rafael Favoretto Silva and Juliana Favoretto Silva – and my friends from all over the world. Life is easier with you.

Last but not least, my grandparents João Pereira da Silva, Olga Cintra, Lucinda Carneiro Favoretto and Getúlio Favoretto (in memoriam), for always being the main source of my strengths and obsessions for new goals.

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Also, Ing. Jirí Korínek, from Prague municipality, for giving access to the North tribune and sharing the documentation available (SPVB and CVUT), and Sr. Miloslav Pytlík, the stadium manager, for gently sharing the keys of the North tribune, and allowing us to freely take photos of the whole area of the North tribune, even the sections that are always blocked for public.

Moreover, my acknowledgments to the architect Ondrej Dusek, who helped me during all bureaucratic processes regarding the achievement of the projects and documents in the Prague City Hall. His efforts not only to get the architectural projects of the stadium but also to translate some Czceh documents were very useful and important for the conclusion of this work.

As well as Dita Frankeová and Lucie Jurkovská for performing thermogravimetric and scanning electron microscopy analysis in samples collected from the Strahov stadium, respectively, and for their insights in the interpretation of the results.

Futhermore, my thanks to the European Program Erasmus Mundus, for offering me a Masters Course scholarship, through SAHC Consortium, allowing me to do the coursework at University of Minho in Guimarães, Portugal, and the thesis dissertation at Czech Technical University in Prague, Czech Republic.

The development of this thesis would never be possible without the classes during the coursework of SAHC Program in Guimarães, Portugal. Therefore, I would like to thank the entire group of professors, especially Paulo B. Lourenço, the head of the so-called "family of SAHC".

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ABSTRACT

Concrete is one of the most relevant construction materials of the 20th century, but both its tangible and intangible values are deteriorating. This work aims to understand the materials, building techniques, and deterioration mechanisms of 20th century concrete buildings, focusing on the Strahov stadium, a landmark building in Prague, Czech Republic. Relevant architectural, historic information, social relevance, and assessment of the current state of conservation was performed for recommending a proposal for further analysis in view of its preservation for future use. The Strahov stadium constitutes a representative *atlas* of the most important concrete damages. The structure is severely damaged by different kinds of anomalies and needs urgent intervention. The two sections of the stadium, which are in a derelict condition (the North and South tribunes) were addressed in this thesis. The main deterioration mechanisms observed in the stadium are related to lack of usage and maintenance. A recent glossary available for the identification of concrete damage types (Monument Diagnosis and Conservation System) was used for the diagnosis and a few recommendations for its improvement were done. A few samples of concrete were collected and analyzed to identify the composition and condition of the materials. Based on the assessment performed, recommendations for further analysis and general preservation and maintenance proposals were made.

Keywords: Reinforced concrete, deterioration, architectural conservation, preventive maintenance.

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ABSTRAKTNÍ

Beton je jedním z nejdůležitějších stavebních materiálů 20. století, ale, jako každý materiál, trpí konstrukčním i morálním opotřebením. Tato práce si klade za cíl porozumět materiálům, stavebním technikám a procesům degradace betonových staveb 20. století, soustředí se na Velký Strahovský stadion, budovu s významem pro celé hlavní město Prahu. V potaz byl brán zásadní architektonický, historický a společenský význam, byly využity dostupné posudky stávajícího stavu. To vše k tomu, aby byl doporučen návrh dalších analýz za účelem zachování budovy pro další užití. V rámci Strahovského stadionu bychom našli řadu důležitých poruch betonu, jakýsi atlas poruch. Konstrukce je vážně narušena různými typy poškození a vyžaduje bezodkladný zásah. Tato práce je věnována jižní a severní tribuně stadionu, dvěma částem budovy ve velmi zanedbaném stavu. Hlavní mechanismy degradace pozorované na stadionu mají příčinu v zanedbání údržby a v absenci využití. Pro diagnostiku byl využit aktuální slovník pro určování typu poškození betonu (Systém diagnostiky a péče o památky). Bylo vysloveno několik doporučení, jak jej vylepšit. Bylo odebráno několik vzorků a tyto byly analyzovány s cílem zjistit složení a stav materiálů. Na základě provedeného posudku byla vyslovena doporučení pro další analýzu a byly vytvořeny návrhy celkové obnovy a údržby.

Titul: Konzervace betonových budov 20. Století – Případová studie Velkého Strahovského stadionu v Praze.

Klíčová slova: železobeton, poruchy, obnova památek, preventivní údržba.

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RESUMO

O concreto é um dos materiais de construção mais relevantes do século XX, mas seus valores tangíveis e intangíveis estão se deteriorando. Este trabalho tem como objetivo compreender os materiais, técnicas construtivas e mecanismos de deterioração dos edifícios de concreto do século XX, com foco no estádio de Strahov, um edifício histórico em Praga, República Tcheca. Informações arquitetônicas, de relevância histórica e social, e avaliação do estado atual de conservação foram realizadas para se recomendar propostas para análise posterior, tendo em vista sua preservação para uso futuro. O estádio Strahov constitui um atlas representativo dos mais importantes danos do concreto. A estrutura é severamente danificada por diferentes tipos de anomalias e necessita de intervenção urgente. As duas seções do estádio, que estão em condição abandonada (as tribunas norte e sul) foram abordadas nesta tese. Os principais mecanismos de deterioração observados no estádio estão relacionados à falta de uso e de manutenção. Um glossário recente disponível para a identificação de tipos de danos no concreto (Monument Diagnosis and Conservation System) foi utilizado para o diagnóstico e algumas recomendações para sua melhoria foram feitas. Algumas amostras de concreto foram coletadas e analisadas para identificar a composição e condição dos materiais. Com base na avaliação realizada, foram feitas recomendações para análises adicionais e propostas gerais de preservação e manutenção.

Título: Conservação de Construções de Concreto do Século XX – O Caso do Estádio Strahov em Praga.

Palavras-chave: Concreto armado, deterioração, convervação arquitetônica, manutenção preventiva.

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1. INTRODUCTION

1.1 Motivations & Scope

Concrete is one of the most important construction materials and is worldwide known among all kinds of societies. Over the years, the production of this material has been substantially increasing. It is nowadays one of the pillars of developed and developing countries. In 90 years, the use of cement increased almost 1700% among the material constructions (Heinemann, 2008).

It is still not sure when exactly the concrete was first produced, but it is believed that it dates back to 12000 years ago, when T-shaped pillars of carved limestone were built in the Turkish temple Gobekli Tepe. Also, around 8000 years ago, some water cisterns were built with concrete in the desert (Courland, 2013). The fact is that, regardless of the exact age of the concrete, it is possible to say that this material plays a great role in the construction techniques since the beginning of the building eras.

The use of concrete has changed dramatically over the last 100 years. These changes follow the improvement of the understanding about the materials and techniques. The industry continues to develop today as experience grows and its versatility and cost-effectiveness is exploited. All these factors determine the durability of the structures, and may result in particular deterioration problems that correlate to the construction period (Stefani, 2014).

Indeed, for the preservation of monuments, one of the most important qualities is the authenticity, and therefore its main mission should always be to make every effort to preserve its original condition as much as possible (Hees, 2014). However, in the field of conservation of modern buildings, there is a kind of parallel sphere of monument care, which, in certain cases, allows interfering with the original structure more than elsewhere.

All around the world, almost all infrastructures rely on the extensive use of concrete, such as bridges, dams, dikes, ports, airports, tunnels, power plants and so forth. Among the synthetic materials on earth, the consumption of concrete and mortar is more than two times higher when compared to the others (Van Damme, 2018). The graphic in Figure 1 illustrates the comparison between the use of cement, steel and plastic from 1950 onwards.

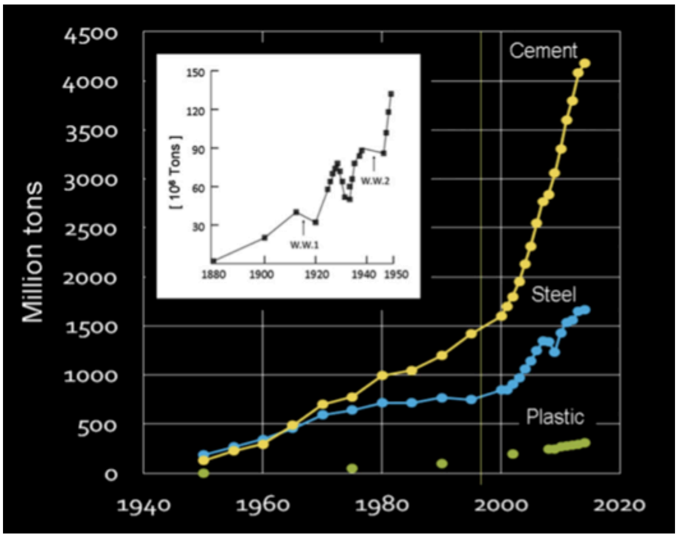


Figure 1 – Consumption of materials over the years **(**Van Damme, 2018).

This graphic illustrates the relevance of cement consumption and, related to the other building materials, it shows the great role it plays in construction (Van Damme, 2018). Thus, maintaining concrete structures is of outmost importance towards a sustainable future.

To maintain the originality of concrete structures, it is important not only to understand the properties of the materials but also to respect some efficient approaches regarding the conservation of their authenticity and integrity. In other words, different approaches may be necessary since buildings evolve over time and new alterations may have different cultural significance (ICOMOS, 2014). It is thus imperative to understand the characteristics of a concrete structure, including its history, and the factors that have affected it since its construction to achieve a correct diagnosis and adequately specify appropriate repair techniques.

Moreover, each country has its own political, economical, social and cultural scenarios. Making alterations in their heritage structures may lead to negative impacts on their cultural environment. Heritage care authorities and historians came to highlight the importance of shifting the concrete repair approach to a conservation approach, similar to that applied in cultural heritage structures built with traditional materials. With the increasing distance to structures and buildings dating from the second half of the 19th century and early 20th century, these were reviewed for their historical significance.

Indeed, there are some conflicts regarding the differences between current approaches and repair techniques. Such conflicts can be related to the typical heritage values (aesthetic, historic and materials), technical challenges, knowledge gaps and other issues such as costs of conservation work and handcrafted approach to industrialized buildings and materials (Baker, 2014).

Another motivation for research was often the threat of demolition or on-going deterioration of former iconic buildings. In general, cultural heritage always contributes to artistic, educational and social development, increasing other activities such as those related with tourism (Assembly, 2018). Thus, preserving concrete heritage buildings can lead to an important improvement of the quality of life of local communities, not only regarding tourists but specially people who interact everyday with it. Moreover, demolition also contributes to the release large amounts of CO_2 in the atmosphere, apart from the waste it is produced.

Hence, the conservation of concrete buildings contributes to the achievement of the following Sustainable Development Goals: No. 9: build a resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation; No. 11: make cities and human settlements inclusive, safe, resilient and sustainable; and No. 13. take urgent action to combat climate change and its impacts.

However, in the context of 20th century buildings, there are many cases in which the only solution for preservation is its documentation. As mentioned, the repair of concrete structures has been mainly based on industry-driven methods and materials, which do not take into account the principles of conservation, like compatibility, retreatability and durability. Yet, in the last decades, several heritage agencies were founded to tackle the problems related to the conservation of modern architecture and are currently operating worldwide, e.g. ICOMOS and DOCOMOMO. More recently, several European research projects aim at innovating conservation methods and materials for historic concrete, e.g. CON-REP-NET, REDMONEST, INNOVACONCRETE and CONSECH20.

The National Heritage Institute in the Czech Republic has developed a number of high-quality methodologies for repairing, remediation and preservation, including several manuals for the conservation of interwar building elements.

The present thesis seeks to contributing to highlight the importance of concrete conservation and was done within the scope of the ongoing European research project CONSECH20 (CONSErvation of 20th century concrete Cultural Heritage in urban changing environments), which aims at developing effective approaches for conservation and protection of 20th century heritage concrete buildings against the ever-changing urban impacts, taking into account both technical and social aspects.

The project focuses on urban contexts with divergent geographical, cultural, political, and economic features. Case studies in four of the participating countries (Cyprus, Czech Republic, Italy, and The Netherlands) will be selected with the aim of gathering a representative selection of architectural styles, periods, conservation state, climate, materials, structural systems, social relevance, etc.

Several case study buildings in the Czech Republic have already been selected for the project. From the list of buildings in Prague, I chose the Strahov stadium as the case study for this thesis not only because of its historical and cultural importance but also because it is a large structure with different types of construction systems that shows many degradation patterns. The stadium itself is an Atlas of concrete damage types that can provide a good background for learning damage processes, conservation and maintenance approaches for concrete cultural heritage. Therefore, the analysis of this stadium can provide me a good background to keep working on the conservation of concrete buildings.

1.2 Aim & Objectives

The main goal of the thesis is the understanding of materials, building techniques, and deterioration mechanisms of 20th cent. concrete buildings focusing on the Strahov stadium, located in Prague, Czech Republic. The objectives to achieve this aim are:

- Identify the leading techniques for surveying, monitoring and conserving modern concrete buildings;
- Investigate all relevant architectural and historical information (including past repair interventions) of the selected case study to support the understanding of material properties and building techniques and their effects on degradation mechanisms;
- Analyze the current state of conservation (condition) of the case study and identify the leading causes of deterioration;
- Validate and possibly contribute to the improvement of the recent glossary available for the description of concrete anomalies Monument Diagnosis Conservation System (MDCS);
- Propose a recommendation for the conservation and preventive maintenance of the case study.

1.3 Tasks

In order to achieve the main aim and the objectives of this thesis, the following tasks were performed:

- The structure of the thesis was discussed and the case study was selected (the Strahov stadium). Then, specific sections of the building were selected, since the construction is very large for the limited time of analysis;
- A complete historical background and a record of all the relevant architectural information was gathered to get a better analysis of the materials and building techniques;
- Analysis of the current state of conservation was performed to identify the deterioration mechanisms and their possible causes of damage;
- Finally, conservation and preventive maintenance proposals were suggested so that the stadium can be revitalized without jeopardizing its authenticity.

1.4 Outline of the Thesis

This thesis is structured in five main chapters. After the introductory section (the present section) follows the state-of-the-art on materials, damage processes, causes of damages, monitoring techniques and conservation techniques. Here, all the concrete materials are described in order to permit a better evaluation of the building techniques of the structure. Also, all damage processes are identified and their respectively causes of damages, so that it is possible to figure the actual condition of the structure. Moreover, the monitoring techniques and the conservation techniques are described in order to get a better view on how to propose recommendations for the case study of the Great Strahov Stadium.

1.5 Delimitations

The idea was to make the conservation proposal based on archive search and visual inspection. One of the positive things about conservation of this type of heritage is that it is possible to find records about the construction techniques and materials used (sometimes the architects and engineers which made it are still alive and it is possible to directly consult with them).

However, it was not possible to physically view all the sections of the stadium under study. The South tribune, for example, was just opened to the public during a single public event, allowing us to take photos of just a part of the structure. The North tribune, on the other hand, was analyzed as its entire pattern but it was needed to collect authorization from the stadium management and the city hall, which took time and bureaucracy.

Overall, despite these delimitations, the analyses were successfully made and the conclusions regarding this work are reliable.

2. STATE OF ART ON DAMAGE, DIAGNOSIS, MONITORING AND CONSERVATION OF CONCRETE

To better analyze the current condition of the stadium’s structure, it is important to identify the main properties of the materials and techniques of this period as well as damage processes and surveying techniques. To extend the lifetime of buildings and constructions at the macro scale, it is necessary to understand the damage processes of building materials at the micro scale. In particular, durability of reinforced concrete structures is one of the most important requirements for construction planning and restoration of concrete buildings. Therefore, degradation mechanisms must be studied and analyzed.

In this section, the materials, damage processes, causes of damage, monitoring techniques and conservation techniques in modern concrete are reviewed.

2.1 Materials

Concrete is basically a mixture of aggregate bounded together by a paste. The paste is commonly constituted by the following materials: Portland cement, minerals, water and chemical additives. In general, a reasonable proportional is about 7 to 15 % of cement, 60 to 75 % of aggregate, and 14 to 21 % of water. The pore network usually represents around 5 to 8 % of the total volume of the concrete. Figure 2 illustrates a scheme of the percentage of the materials that constitute the concrete. This general concrete composition must be respected in order to avoid future structural damages e.g. buckling, creep, deformation, Poisson coefficient and global stability of the structure. These types of pathologies can be severe and expensive to the construction site, and lead to unwanted expenses over time. Unfortunately, many construction companies rather spend less money in concrete processes and pretend their cost of construction will be decreased. Some even disregard the correct traces of the concrete and accepts higher level of water or lower level of cement. In the following sub-sections, the main components of concrete are analyzed in detail.

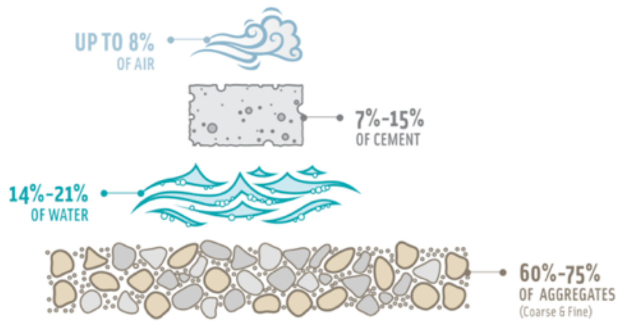


Figure 2 – Concrete composition.

2.1.1 Aggregates

The main types of aggregate used are sand, gravel and crushed stone. In general, the aggregates can be commonly categorized as sand and coarse (generally fine in texture). They differ in sizes and act as a strengthening to the composite material (Secco, 2019), and are mainly composed of monocrystalline and polycrystalline quartz, fragments of silicate stones and sporadic feldspar crystals (Ozga, 2011).

As previously stated, the aggregates represent the greater proportion in concrete. They play an important role in the strengthening and durability of the concrete. Crushed limestone is the most common type of stone that constitutes the aggregates (Macdonald, 2003). Figure 3 illustrates crushed limestone and coarse grained sand.

Figure 3 – Crushed limestone and coarse grained sand (Hees, 2014).

As the aggregate particles are not always able to totally fit in their dimensions due to manufacturing processes, a void is created in the interface between the aggregate and the cement paste. This void is a thin area that that can represent up to 30% of the total volume of the concrete (Scherer, 2015). The interface between the aggregate and the paste is designated as interfacial transition zone (ITZ) and will be discussed further in this section.

2.1.2 Portland Cement

The most common type of cement used in concrete is the Portland cement, which is based on a mixture of clinker (ca. 90%), calcium sulphates ($CaSO_4$) and other minor constituents. The main qualities of Portland cement are fast hardening, sulphate-resistant and low heat generation, which benefit the concrete processes (Lau, 2016).

The most common way to commercially manufacture Portland cement is through a dry method, by mixing limestone with particles of clays. The whole process consists of five steps: quarry, crusher, rotary kiln, heating and cooling, as illustrated in Figure 4. In the first step, the limestone – a sedimentary rock basically constituted of calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) – and the clay – particles that contain alumina (Al_2O_3), silica (SiO_2), lime ($Ca(OH)_2$), iron oxide (Fe_2O_3) and magnesia ($Mg(OH)_2$) – are quarried. In the second step, rock materials are crushed into smaller pieces. This process consists of two crushes: the first crush reduces the rock to a maximum size of about six inches and the second one reduces to a maximum of three inches. Then, in the third step, the crushed limestone and clay are grounded and mixed together through a rotary kiln. The limestone, when heated together to high temperatures (1300-1500ºC), produces lime (CaO) by eliminating carbon dioxide (CO_2) from the calcium carbonate ($CaCO_3$). The clinker then is cooled and mixed with small amounts of gypsum and limestone (Macdonald, 2003).

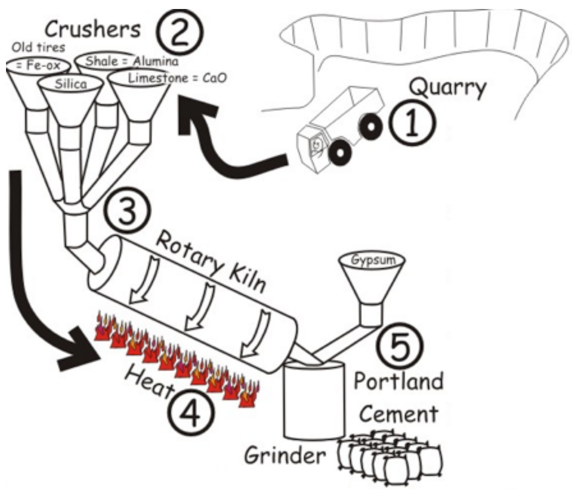


Figure 4 – Portland cement formation.

The hydraulic properties of the concrete are provided by the components in the clay particles. By melting the particles of silicates ($Si_2O_5^{2-}$), aluminates ($NaAlO_2$) and aluminosilicates ($AlNa_{12}SiO_5$), in the form of a clinker, they can be chemically combined by a heating process. Then, this mixture is finely grounded to a powder and, mixed with water, is able to originate the cement paste. (Secco, 2019).

The reaction produced between the binder and the water leads to the formation of an alkali paste that involves the aggregate as a solid mass. The clinker itself, as its original formation, can have two typical phases: the hydrated phase and the non-hydrated phase. Both hydration processes are related to the strength of the concrete (Fatiguso, 2013).

2.1.3 Reinforced Concrete

Reinforced concrete is basically a concrete material with embedded steel bars, acting together as resisting forces and increasing the ductility of the material. Overall, the reinforcing steel absorbs the tensile and shear stresses of the structure, while the concrete absorbs the compressive stresses. Therefore, the invention of the reinforced concrete in the 19th century marked a new era on the construction history, since reinforced concrete structures would be able to sustain the stresses over substantial spans.

It is believed that the first reinforced concrete house was built in 1853 by François Coignet. Design details can be seen in Figure 5. However, there were no scientific experiments proving the efficiency of such innovative material. It took a while for the scientists to report analyzes on the behavior of reinforced concrete. Decades later, in the end of the 19th century, Ernest L. Ransome made significant improvements in all styles and techniques of the previous known inventors, improving conditions for fireproof design for example. In 1879, G. A. Wayss, a German civil engineer and a pioneer of the iron and steel concrete construction, started the first commercial use for reinforced concrete.

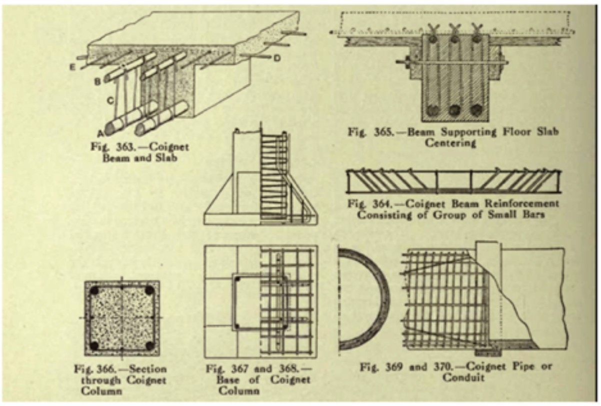


Figure 5 – First reinforced concrete design.

In general, reinforced concrete was widely used during the second half of the 19th century. Another architect that deserves merits regarding concrete innovations is the French professional A. Perret, who built one of the first concrete complexes with a structural frame totally made of reinforced concrete. This material soon became the most used construction system by architects and engineers, who were fascinated with its great mechanical properties and low production costs (Secco, 2019). Last, but not least, François Hennebique also deserves merits, for inventing the Hennebique system (Figure 6), one of the most important reinforced concrete construction systems in modern architecture.

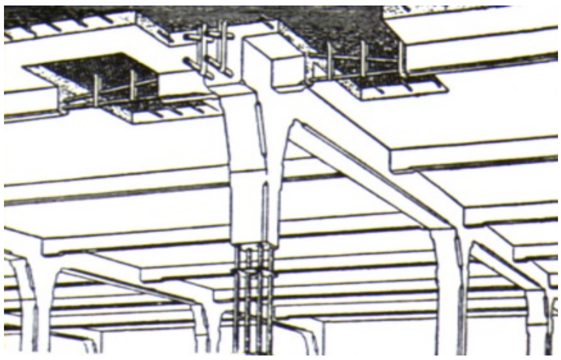


Figure 6 – Hennebique System.

Non-reinforced concrete subjected to strain and stress can lead to structural damages like cracks, creep, buckling, deformation and so forth (Heinemann, 2010). These damages are due to the alteration of the Modulus of Elasticity, Young's Modulus and Poisson Coefficient, since these factors directly affect the rigidity and stability of the structure.

Despite all advantages of reinforced concrete composites, there are also weaknesses since they can be sometimes brittle and liable to crack. To avoid this drawback, concrete can be prestressed, i.e. tensing the steel bars before embedding into the wet concrete, or by poststressing the steel bars after it hardens. Figure 7 illustrates the difference between both reinforced and prestressed concrete. Both scenarios have the same constituent materials (concrete and steel); they only differ on the way to develop the procedures. In the first case (reinforced concrete), the steel is tensioned after being covered by the concrete, while in the second case, the steel is tensioned before getting stressed.

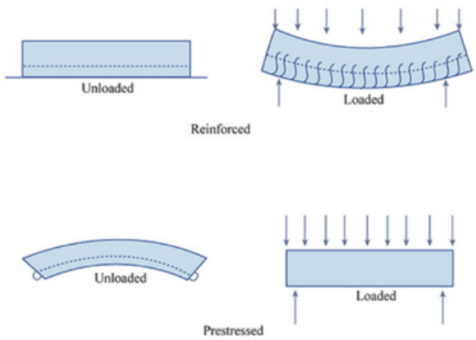


Figure 7 – Reinforced/prestressed behavior.

Overall, reinforced concrete can be used in all kinds of structural elements, e.g. slabs, walls, beams, pillars, foundations and so on. In the construction scenario, reinforced concrete can be used either by precast or cast-in-place technique.

2.1.4 Water

Water plays a key role in the hydration process of cement. It is important to ensure that the water is free of contaminants that may affect the performance of the concrete. Figure 8 reveals a correlation study between water/cement ratio and compressive strength (Secco, 2019). The water/binder ratio is inversely proportional to the compressive strength of the concrete because high quantities of water reduce the modulus of elasticity of the concrete. An appropriate water/cement ratio should be within the range 0.38 to 0.42 (Secco, 2019). If on the one hand, high water/binder ratios lead to lower compressive strength, on the other hand, low ratios can substantially increase the production costs, since concrete consumption would increase, and also turn the concrete into a bad hydrated structure. The amount of water determines not only the workability but also the hardened properties (e.g. compressive strength, permeability, durability) (Kosmatka, 2011).

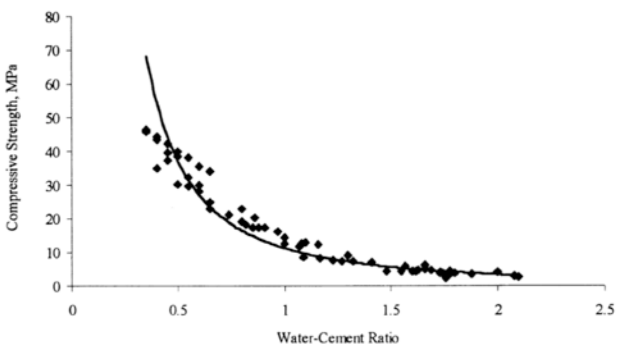


Figure 8 – Water/cement ratio.

2.1.5 Chemical Admixtures

Chemical admixtures act on several rheological properties of the concrete, thus also influencing the hardened state. They can be added before or during the mixing processes and can be either organic or inorganic. The most common organic admixtures for concrete are plasticizers or super plasticizers. These materials, working as water-reducing agents, began to be used in the decade of the 1930s but started to be commercially used in large scale 40 years later (Secco, 2019).

They are able to improve the hydration reactions of the cement and workability, since they can modify the viscosity, act in the reduction of water, accelerate or delay the curing time, control the development of mechanical resistance and reduce drying shrinkage. Overall, plasticizers can increase the fluidity of the concrete thus allowing to reduce the water demand (Leemann, 2007).

However, these water-reducing additives and retarders must be added according to the building codes. Irregular additions of these chemical admixtures can increase the basic creep of the concrete, making the structure prone to Ultimate Limit State (ULS) and Serviceability Limit State (SLS) failures, directly impacting the global safety of the structure (Favoretto, 2019).

In general, super plasticizers can be constituted by negatively charged polyelectrolytes designed to avoid floc formation, and also absorb on other fine particles such as silica fume (SiO_2) or on the positively charged surfaces of the dissolving cement particles (Van Damme, 2018).

2.1.6 Pore Network

Representing from 10 to 30% of the total volume of the concrete, the pore network plays a key role on the mechanical performance and durability of concrete. The pore sizes can be classified as micropores, mesopores, and macropores (IUPAC). Additionally to this classification, it is useful to consider the pore size in relation with moisture transport, for instance, capillary pores range from 0.1 to 100 μm are formed during the process of binder hydration, on areas previously occupied by water. Voids can also develop when the cement is mixed with water, due to the inclusion of air bubbles in the binder (Secco, 2019).

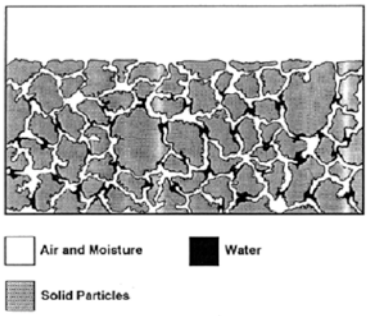


Figure 9 – Pore network.

Voids can absorb tensile stresses caused by freezing-thawing cycles, hence air entraining admixtures are often employed in the production of concrete to be applied in cold climates (Chatterji, 2003). Figure 9 represents the presence of pore network in a concrete structure. The pore size distribution varies from nanometers to microns and is always concentrated in the interior of the cement since the aggregate solid particles are not totally connected due to their surface imperfections. Thus, a large amount of air bubbles emerge, originating the area called pore network. Generally, concrete is composed of non-porous aggregate, a finely porous cement paste and the so-called interfacial transition zone (ITZ) between cement paste and aggregates. The ITZ has a great impact on the concrete mechanical behavior (Song, 2017).

Overall, compared to the ITZ, the cement paste of the concrete has much finer porosity. These nanometric pores can be analyzed through electron microscopy techniques, e.g. Scanning Electron Microscopy (SEM), Scanning Transmission Electron Microscopy (STEM), X-Ray tomography or ptychographic imaging.

The scanning electron microscope (Figure 10) is an electron microscope that produces images of a sample by scanning the surface with a focused beam of high-energy electrons. The interaction between electrons and atoms in the sample produces several signals that contain information regarding the surface topography and composition of the sample. The electron beam is scanned and positioned according to the intensity of the detected signal to produce an image.

In general, the electron interaction can produce several types of signals, e.g. secondary electrons, reflected or back-scattered electrons, characteristic X-rays and light (cathode-luminescence), absorbed current and transmitted electrons. In all SEMs, secondary electron detectors are standard equipment, but it is rare for a single machine to have detectors for all other possible signals. In the most common SEM mode, secondary electrons emitted by atoms excited by the electron beam are detected using an Everhart-Thornley detector. The number of secondary electrons that can be detected, and thus the signal intensity, depends, among other things, on specimen topography. Overall, SEM can achieve resolution better than 1 nanometer. In conventional SEM, specimens are observed in high vacuum, or in low vacuum or wet conditions in variable pressure or environmental SEM, and at a wide range of cryogenic or elevated temperatures with specialized instruments.

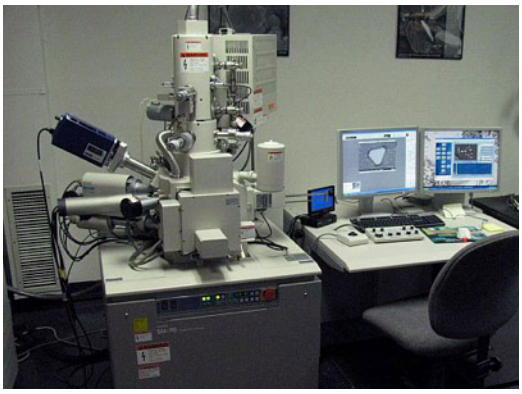


Figure 10 – Scanning electron microscope.

2.2 Damage Processes & Causes of Damage

In this section, the most relevant damage processes and respective possible causes in concrete are reviewed to help understanding how to prevent and repair such deteriorations. In general, the occurrence of damage is the result of several deterioration processes acting together.

Failure to recognize and mitigate all the causes of damage will most likely result in poor repair serviceability. In fact, it is essential to understand which are the weakening causes and the accelerated causes of the damages, so that it is possible to priorize the most urgent approaches. The selection of the proper methods and materials for repair and maintenance of a damaged concrete structure depends on their respective deterioration causes. A mistaken analysis and repair technique can sometimes worsen damage mechanisms.

Concrete degradation is mainly affected by external factors. They can be related to either chemical, physical or mechanical deterioration mechanisms (Secco, 2019). In general, the main deterioration mechanisms found in concrete structures are acidic attack, reinforcement corrosion, internal expansive reactions, delayed ettringite formation, thaumasite formation, salt crystallization, freeze-thaw cycles, excessive structural deformation, design, fabrication and execution flaws.

2.2.1 Acidic Attack

Portland cement has high alkalinity (pH above ca. 12), hence it is very vulnerable to suffer acidic attack. During this damage process, both hydrated and un-hydrated cement compounds are dissolved.

The acidic compounds are mainly originated in environments with high levels of air pollutants, e.g. nitrogen (N), sulphur oxides (SO_2) and carbon (CO_2). The dissolution and leaching processes resulting from acidic attack reduce the cohesion and the mechanical properties of the material. The pH values of the cement paste decrease almost 50%, reaching levels of 6.5 (slight aggression), 5.5 (severe aggression) and 4.5 or even less (very severe aggression). Sulfuric acid (H_2SO_4) attacks (Figure 11) can originate extensive formation of gypsum in the regions close to the concrete surfaces, due to the low penetration of sulfuric acid in the interior of the concrete structure. This causes disintegration and mechanical stresses, which automatically leads to the formation of spalling and exposure of the fresh interior surface. However, in very severe acid aggression, it is also possible to observe scaling and softening of the concrete, due to the early decomposition of calcium hydroxide ($Ca(OH_2)$) and the consequent formation of large amounts of gypsum (Jamal, 2017).

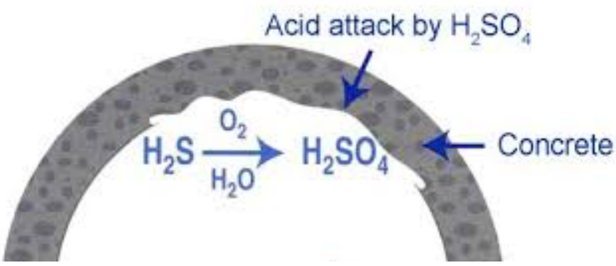


Figure 11 – Sulfuric acidic attack.

In general, the cement compounds are insoluble, thus granting protection against structural alterations. During the acid attack, the cement particles are dissolved, hence exposing the concrete surface and leading to possible cracks due to the development of tensile stresses (Secco, 2019).

2.2.2 Reinforcement Corrosion

A very common and important deterioration mechanism in concrete structures is the reinforcement corrosion. It can be triggered either by carbonation of the concrete or by chloride attack. The carbonation is the main cause of chemical degradation in reinforced concrete and, when steel corrodes, the resulting rust occupies a higher volume than the steel (Figure 12). Thus, tensile stresses are created in the concrete, leading to possible cracking, delamination and spalling. Steel is thermodynamically unstable under normal atmospheric conditions. When there are two or more metals at different energy levels, an electrolyte, and a metallic connection, corrosion may occur. The steel will thus return to its original state, as an iron ore, releasing energy to the metal (PCA, 2002).

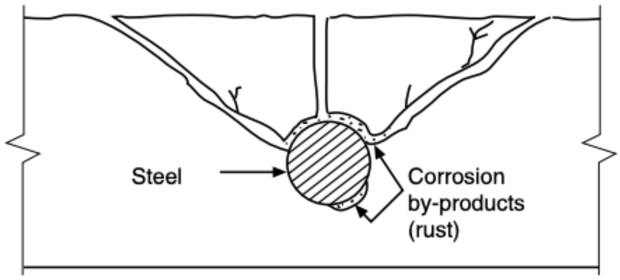


Figure 12 – Reinforcement corrosion.

Due to low levels of pH, carbonation comes as the main cause of reinforcement corrosion. In cases when pH level is higher than 12, a thin layer of iron oxides is formed around the rebars, covering the steel bars with magnetite and ferric oxide (Fe_2O_3) layers before casting. The low levels of pH unprotect the concrete surface (Secco, 2019).

Chloride attack involves the penetration of chlorides into the concrete through the pore network, forming an oxide film over the reinforcing steel rebar. Chlorides can also present in the concrete components from the beginning (for instance, use of sand or water contaminated with chlorides).
In general, when exposed to different environmental conditions, the reinforced concrete structure is prone to suffer corrosion attack. In this mechanism, an electrochemical process occurs, either by the presence of different metals in concrete (e.g. steel rebars, aluminium conduit pipes), or by cell formation near the reinforcing steel (Quraishi, 2017).

Corrosion is basically an electrochemical process involving the flow of charges (electrons and ions). In reinforced concrete structures, the steel bars present different levels of energy and the concrete acts as an electrolyte. The flow of electrons and ions of the iron atoms causes anodic reactions in the concrete and consequently releases energy in the interior of the material, as seen in Figure 13. Then, the cathodes and anodes of the iron bars will react to energetically balance the system, leading to the formation of internal stresses within the concrete and possibly causing cracks and spalling on the concrete surface. Summarizing, steel corrosion is a two-step process. In the first process, iron atom at the metal surface dissolves into the moisture film, negatively charging the metal. Then, in the second process, a depolarizer removes electrons from metal, increasing the corrosion mechanism. The most common depolarizers are oxygen, acid and cation of more-noble metal (PCA, 2002).

The corrosion attack on steel has become a serious problem, with high costly repairs. When the concrete presents corroded steel bars, its durability is substantially decreased, leading to structural failures of the material. Therefore, it is extremely important to protect concrete from reinforcing corrosion and, if this damage is already presented in the structure, urgent repairs must be done in order to avoid further complications.

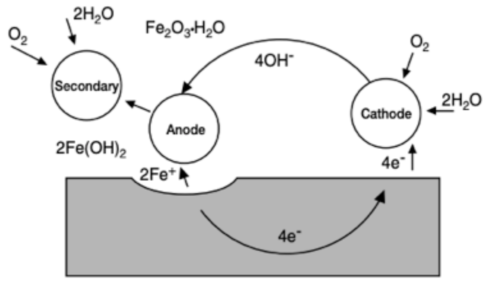


Figure 13 – Concrete anodic reactions.

Indeed, there are many electrochemical and non-destructive techniques available for measurement of the corrosion rate of reinforcing steel in concrete. Rebar corrosion on existing reinforced concrete structures can be assessed by different methods, such as: embeddable corrosion monitoring sensors, ultrasonic pulse velocity measurements, open circuit potential measurements, vibrating wire and electrical strain gauges, harmonic analysis, galvanostatic pulse transient method, X-ray/gamma radiography, electrochemical impedance spectroscopy, infrared thermography, cover thickness measurement, optical fibre sensors, visual inspection, tafel extrapolation, electrochemical noise analysis and so forth (Zaki, 2015).

2.2.3 Internal Expansive Reactions

The internal chemical mechanisms of deterioration are related to the reactions between alkali aggregate and internal sulfate reactions. These substances, present in the interior of the concrete, usually migrate towards reactive substances, originating internal expansive reactions. This mechanism is mostly caused by the presence of water in concrete, also in gaseous phase.

As mentioned previously, there are many types of mineral aggregates, alkali and hydroxyl ions (OH^-) in the cement paste. These materials internally react with each other, causing chemical reactions that affect the energetic balance of the structure, consequently leading to the development of internal stresses. These stresses can cause cracks, efflorescences and exudations on the surface of the concrete (Antunes, 2010).

Overall, the main factors that promote these internal chemical reactions are related to the alkalinity of the solution, the existence of reactive aggregates and moisture. Indeed, the higher the alkalinity of the concrete's solution and the higher the humidity of the environment to which the structures is exposed, the more prone it is to suffer these internal reactions.

Moreover, when these reactions occur, the volume of the material is increased, also causing the formation of ettringite (described in the next sub-section) that contains expansive properties under certain thermodynamic conditions. Other factors supporting expansive reactions are high temperature, high content of alkalis, and high content of calcium hydroxide ($Ca(OH_2)$) in the cement paste (Antunes, 2010).

2.2.4 Delayed Ettringite Formation

Perhaps the most important form of internal sulfate attack in reinforced concrete structures is the delayed ettringite formation (DEF) which can be caused either by internal causes (e.g. hydration of the cement paste) or by external causes (e.g. steam-curing). When this deterioration mechanism occurs, internal stresses are triggered in the interior of the concrete structure leading to internal cracks and loss of cohesion.

Ettringite was first described in 1874 by J. Lehmann as an hydrous calcium aluminium sulfate mineral formed in hydrated Portland cement system as a result of the reaction between calcium aluminate ($CaAl_2O_4$) and calcium sulfate ($CaSO_4$).

Normally, ettringite is one of the first phases forming in the hydration process of the concrete. However, with increasing temperature (reaching 65°C) ettringite becomes unstable and the formation of the primary ettringtite is inhibited. Then, the constituents of ettringite, after being dispersed as monosulfate and calcium silicate (Ca_2O_4Si), form the secondary ettringite (Figure 14). The secondary ettringite is formed when the concrete is alreay hardened and the thermodynicamic conditions are favourable (e.g. low temperature and sufficient humidity). However, the formation of the secondary ettringite results in the expansion leading to concrete cracking. Indeed, the cement paste, under low levels of temperature with available moisture, suffers expansion and consequently forms cracking on the surface of the concrete. In general, the DEF-induced cracks are considered peripheral cracking, since cracks propagate around the aggregate particles not previously cracked. These cracks become, then, filled with secondary ettringite crystals (Larosche, 2009).

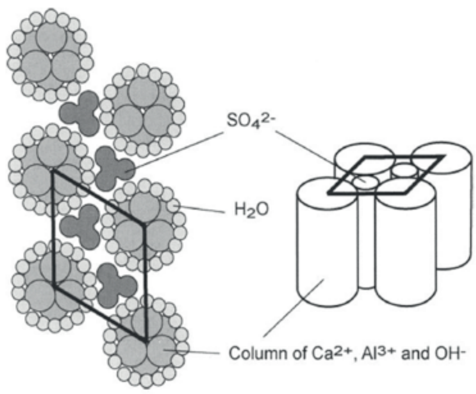


Figure 14 – Ettringite formation.

These reactions decrease the level of pH to around 10.5. To energetically balance this scenario, calcium silicate hydrate dissolves forming portlandite. Furthermore, hydrated magnesium silicate is formed by the junction of gypsum and the delayed ettringite formation (Secco, 2019).

2.2.5 Thaumasite Formation

Thaumasite is a silicate mineral that takes several years to form in reinforced concrete structures. In general, thaumasite can be directly formed by calcium silicate (Ca_2O_4Si), gypsum and calcium carbonate ($CaCO_3$). In environments with low level of temperature, high level of humidity and substantial presence of cabon dioxide (CO_2), the sulfate reacts with the gypsum causing the formation of thaumasite (Matshcei, 2015).

The formation of thaumasite leads to the occurrence of tensile stresses, caused by the high crystallization pressure of the concrete, and calcium silicate hydrate (CSH) consumption, related to the disaggregation of the cement paste, similar to what happens with the delayed ettringite formation (Secco, 2019). In fact, sometimes it is difficult to distinguish secondary ettringite and thaumasite because they have similar crystal morphology even when observed under the Scanning Electron Microscope (SEM). Therefore, it is important to complement the analysis with compositional identification techniques such as Energy-Dispersive X-ray Spectroscopy (EDS) (Yuanming, 2017).

To transform the CSH phases into thaumasite, the hydroxide concentration and alkalinity must be taken into account. Indeed, the concentration of hydroxide determines the minimum required sulfate ion concentration. Moreover, the higher the pH values of the substance, the higher the concentration of sulfate ion up to which the CSH phases are immune to the formation of thaumasite. Indeed, chemical resistance is affected by the alkalinity of the pore solution. Due to leaching, the highest levels of pH are observed in the reaction point and the lowest levels are found in the unaffected core of the concrete. These pH differences can significantly destabilize a system, possibly leading to the formation of thaumasite. The process of carbonation of the leaching zone may solve, or at least, reduce the problem (Bellmann, 2007).

2.2.6 Salt Crystallization

Salt crystallization is basically influenced by the following factors: solubility, concentration, air pressure, temperature and relative humidity. As with the delayed ettringite and thaumasite formations, these factors lead to a high level of tensile stress on cement, consequently causing cracking, exfoliation and spalling of large areas of the concrete. This degradation mechanism usually occurs in the external surface of the concrete structural elements, influenced by a significant difference in temperature and humidity, leading to a high level of water evaporation and consequently salt crystallization (Secco, 2019).

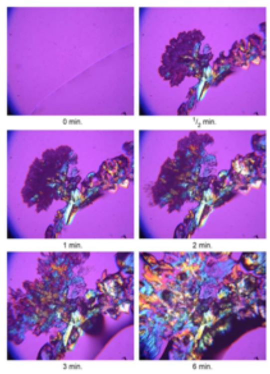


Figure 15 – Salt crystallization.

Crystallization occurs in two major steps. The first one is the nucleation, where the crystalline phase appears from either a super cooled liquid or a supersaturated solvent. The second one is the growth of the crystal, by the increase of the particles size, leading to a crystal state. An important feature of this process is that all lose particles from layers at the crystal's surface are considered pores and cracks. The supersaturation, an important condition for the crystallization, can be observed in Figure 15, taken from an experiment that reveals that the evaporation of liquid can also create super saturation. In this case, sodium sulfate crystals grow at a sodium sulphate solution and air interface, slowly decreasing the area of the solution and turning the material into mirabilite (Thaulow, 2004).

2.2.7 Freeze-Thaw

When water freezes, its volume increases about 9% during the transition from liquid to solid state, resulting in the development of pressure on pore walls of the concrete. This pressure usually occurs in small saturated pores, such as the capillaries, since they do not have enough space to support volume changes. If this pressure overcomes the tensile strength of the concrete, the cavity will suffer dilatation and rupture over time. In general, the use of deicing salts in cold seasons can be useful against freeze-thaw cycles (Secco, 2019). However, some of the salts can also be harmful; in Czech Republic, for instance, the use of sodium chloride (NaCl) is very common in roads and highways.

If not treated, the cumulative process of freeze-thaw cycles will lead to disruption of the cement paste and aggregate, eventually causing significant expansion and cracking, scaling and crumbling of the concrete. Here comes the importance of entrained air voids and pore network. Whenever there is a water expansion due to freeze-thaw, the air voids act as internal empty chambers in the cement paste (Figure 16). Thus, the pressure inside the concrete, more specifically in the capillaries and pores, is reduced, preventing structural damages in the concrete. Also, as the permeability is directly related to its water/cement ratio, low permeable concretes are less prone to suffer with freeze-thaw deterioration (PCA, 2002).

Figure 16 – Freeze-thaw.

Freeze-thaw is a deterioration mechanism that occurs in concrete structures exposed to cold climates and, in order to evaluate the damages caused by freeze-thaw deterioration, the ice formation process in concrete pores and capillaries must be well analyzed. The volume, radius and size distribution of pores indicate the freezing point of pore solution and the amount of ice formed in pores. Furthermore, the increase in temperature does not change the ice content in concrete, since the pore thaws before the temperature rises near 0ºC (Cai, 1998).

The proper use of air entraining admixtures in modern concrete has greatly increased the resistance of the concrete to freeze-thaw deterioration. Nevertheless, freeze-thaw deterioration is often still blamed as a relevant cause of damage in modern concrete (Macdonald, 2003).

2.2.8 Excessive Structural Deformation

When concrete is subjected to long and excessive load duration, the deformation increases over time, causing creep. Therefore, the deferred displacement when creep and retraction effects occur must be determined as soon as the immediate displacement of a piece of reinforced concrete is obtained (Favoretto, 2019).

The excessive structural deformation is a deterioration mechanism that occurs due to the lack of seismic design or thermal dilation. Early concrete structures often lack dilatation joints and, in concrete subjected to loading, as in several other materials, the deformations can be severe.

In general, deformations can be elastic (reversible), viscoelastic (partially reversible, consisting of a viscous and an elastic phase) and plastic (non-reversible), as seen in Figure 17. The elastic deformation is instantaneous, linear and always recoverable with the unloading. The plastic deformation is instantaneous, irreversible, without volumetric variation of the material and there is no proportionality between plastic deformation and applied stress, or between tension and strain velocity. The viscous deformation is irreversible in the unloading, always depends on the time and there is proportionality between the viscous deformation speed and the applied tension. In addition to deformations due to the applied load, there are inherent deformations of the concrete caused by loss of water, delayed deformation by retraction.

In case of nonconformity of concrete, the modulus of rigidity tends to decrease, since the material with decreasing compressive strength presents greater vulnerability for deformations relative to shear stresses. Also, the Young's modulus also undergoes subtraction when nonconformity occurs. Therefore, the structure must be sufficiently rigid so that its deformations, under the action of the service loads, do not cause excessive damages in structural elements, do not affect its use or appearance and do not negatively impact the global stability.

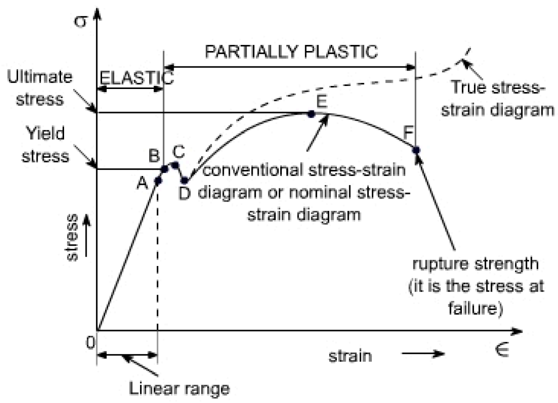


Figure 17 – Stress/strain diagram.

2.2.9 Design, Fabrication and Execution Flaws

For a durable construction, a set of decisions and procedures must be adopted that guarantee the structure a satisfactory performance throughout the useful life of the construction. The pathologies in the design phase of the project can be originated during the preliminary study. The executive design may arise during the execution of the project, or in the elaboration of the final engineering project (Favoretto, 2019).

Among design faults, the most common in modern concrete constructions are: improper location of reinforcement; lack of transverse bracing and their poor adherence with working; poor grip of metal by concrete caused by the use of smooth reinforcing rods; inadequate reinforcement; the use of stiff concrete; construction in environmental temperatures below zero; dehydration of concrete mixtures cast in hot weather without special curing; improper intervals between the stages of concrete casting; negligence in making and using concrete forms; accidental overloads at construction; misuse of materials for reinforced concrete structures and so forth (Souponitski, 2001).

Another very important design flaw is related to incorrect load calculations that can lead to the appearance of overloading tensile stresses on structural elements, resulting in deformation and creep, and subsequent chemical, physical and mechanical deterioration. Therefore, it is extremely important to respect all Engineering codes. Understanding all deterioration mechanisms in order to perform an accurate analysis of concrete degradation due to design irregularities, improper fabrication or execution flaws, and also failures in past interventions, like the use of incompatible repair materials, is vital to secure a safety global stability (Secco, 2019).

The concrete structure may be damaged by faulty design and construction techniques. Built heritage is subjected to a never-ending process of modification and transformation due to past and current anthropogenic interaction, past interventions, poor site practice and poor performance in use. Past interventions are a common source of damage due to the use of incompatible materials and techniques. Changes in use and lack of maintenance are other factors that can accelerate the degradation of the buildings

2.3 Survey & Monitoring Techniques

Monitoring the global conditions of buildings is imperative to ensure structural durability and safety. It allows increasing the safety margins without any intervention on the structure. Indeed, building structures that endured in good conditions until nowadays are supported by appropriate management and maintenance plans. Recently, several recommendations have been reported for repairing and maintaining modern concrete constructions. These should serve as guides to design interventions in particular buildings (Inaudi, 2002).

In this section, survey and monitoring techniques are reviewed to aid in the design of maintenance plans for concrete buildings. The main relevant monitoring techniques commonly used concern damage and geometry mapping, displacements and deformations, cracks, internal structure, mechanical properties, transport properties, and structural assessment.

2.3.1 Damage & Geometry Mapping

In many cases, an efficient geometry mapping gives a very helpful background, as a starting point, for performing a diagnosis. The geometry map can then include information from visual mapping of damage, e.g. spalling, cracking, delamination, deformations and other physical alterations in the concrete structure surface (Albrektsson, 2011).

In order to perform a damage map, damage glossaries must be respected. In fact, there are many different types of damage and they can be quite difficult to be distinguished sometimes, since they often act together with other deterioration mechanisms. In other words, in the same critical area of the structure, it is possible to figure a substantial number of different damages, which can hinder the identification process of possible causes of damages.

For instance, the Monument Diagnosis and Conservation System (MDCS) is an interactive tool for the inventory and evaluation of damage to monument buildings, which recently included concrete constructions. Indeed, MDCS is one of the main keys of this thesis, since its applicability is verified in the Strahov Stadium. The tool is very useful to identify damages and their possible causes. Through MCDS, it is possible to identify the types of materials and types of damages and, based on these types, the possible causes of damages can be discovered and a consequently diagnosis of conservation can be planned. It is the first glossary to describe concrete degradation forms, which are under analysis on the CONSECH20 project.

Damage mapping is the first step in the assessment of the condition of a structure as it provides the ground for planning further analysis. The damage mapping gives support on the analysis of the results and analysis techniques. Therefore, it is essential to understand all causes of damage in order to evaluate the best possible solutions. Sometimes, it is also advised to use some tools to better evaluate the structure conditions, e.g. photogrammetry and 3D scanning.

2.3.2 Displacements & Deformations

Many reinforced concrete structures face problems with displacements and deformations. This is a common anomaly in structures that are not well maintained. To monitor these types of damage, some onsite monitoring tests can be performed, e.g. tilt meters, settlement measurements, plumb line, inclinometer.

The tilt meter (Figure 18) is one of the main tools for monitoring deformation; it is a sensitive inclinometer designed to measure very small changes from the vertical level, either on the ground or in the structure. In general, concrete structures with deformation and displacement problems usually call for a need of constant monitoring, which can be achieved by the installation of tilt meters, displacement transducers, and ambient detectors to attain continuous data about the condition of the structure.

Figure 18 – Tilt meter.

Since concrete is not a homogeneous material, it is recommended to use long-gauge deformation sensors for its structural monitoring (Figure 19). This technique will lead to accurate information concerning global structural behavior of the structure. Moreover, as concrete is also subjected to substantial dimensional and structural changes during the hydration process, it is recommended to embed the sensors in the structure.

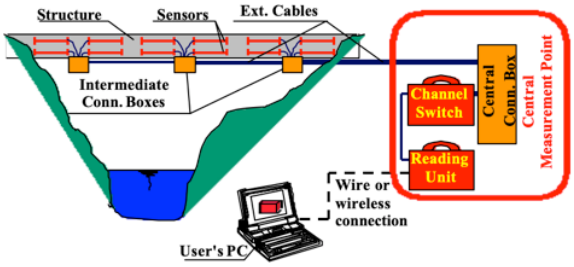


Figure 19 – Long-gauge deformation sensors.

It is always necessary to employ good monitoring strategy and the type of sensors should be selected depending on the structure and respective expected loads. A good monitoring strategy can prevent many problems with a relatively limited budget (Inaudi, 2002).

2.3.3 Cracks

Another common damage in concrete structures is the formation of cracks. Their appearance should be monitored to avoid severe stability issues. Depending on the observed phenomenon, adequate key parameters must be selected (e.g. temperature/humidity, crack opening, modal frequencies).

There are several methods available for monitoring cracks, e.g. crack meter, acoustic emission, linear variable differential transformer (LVDT – Figure 20). One common monitoring technique for cracks is the crack pattern evolution, which is usually a slow but efficient process. It can be performed daily, weekly, monthly, yearly etc. depending on the necessity of the analysis (Lourenço, 2019). Moreover, to propose efficient recommendations for monitoring crack evolution, it is necessary to divide them into different categories, e.g. width, depth, pattern. To separate cracks automatically, their geometry has to be considered. Small-scale cracks, for instance, can be considered as thin plates. For this, different crack detection methods are available.

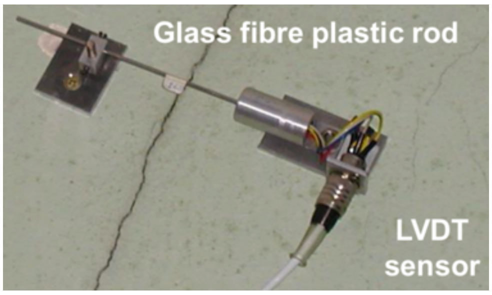


Figure 20 – LVDT sensor.

Overall, monitoring the changes in crack width is an important diagnostic technique for determining the cause and specifying the remedial work. For thin cracks, template matching is the method with the best results, but the computation time is quite long. The so-called Hessian-driven percolation is more suitable and able to detect bending and branching cracks. The number and shape of detected cracks in all methods depends on the different software parameters (Nijland, 2010).

2.3.4 Internal Structure

For non-destructive (or quasi non-destructive) analysis, the on-site test methods can be the ultrasonics, ground-penetrating radar, electrical resistivity tomography, infrared (IR) thermography, laser holography interferometry, sponge method, Karsten pipe, Scotch tape test, drilling resistance, test strips, Schmidt Hammer, colour measurements and profilometer.

And regarding the destructive tests that require sample collection, it is possible to state the laboratory-based methods for material samples can be the polarized light microscopy, ion chromatography, hygric test, mechanical strength, computerized X-ray tomography and biological methods. Petrographic observations, for instance, using a polarizing microscope, allow characterizing the textural features of concrete samples (Marinoni, 2003).

Sometimes, reinforced concrete structures represent internal damages that are not seen by naked eye. Therefore, it is important to make use of techniques which enable observing the internal structure, e.g. impact-echo, infrared thermography, elastic wave tomography, ground penetrating radar (GPR), thermography.

Overall, thermogravimetric analysis (Figure 21) is a method of thermal analysis that monitors the mass of a sample against time or temperature, investigating the thermal performance of nanocomposities of the sample. This measurement can provide information regarding physical phenomena, e.g. absorption, adsorption, desorption and phase transitions. The analysis was carried out with a TA instrument, model SDT Q600 TGA/DSC in static nitrogen atmosphere at a temperature range between 20 and 1000°C and at a controlled heating rate of 20°C/min.

Figure 21 – Thermogravimetry.

In general, thermogravimetric analysis relies on a high degree of precision in three measurements: weight, temperature, and weight change with temperature. This analysis aims to measure degradation temperatures, the level of inorganic and organic components in materials, decomposition peaks of temperature and residues (Groenewoud, 2001).

Ground penetrating radar (GPR) consists in applying high frequency electromagnetic wave transmission in the structure, as seen in Figure 22. The wave will propagate into the medium and then be reflected at the interface between different environments. For this monitoring technique, it is necessary to use a transmitter, a receiver, an antenna, and connect them to the surface of the concrete structure (Courard, 2012).

Using GPR over other methods has many advantages including quiet operation, no health hazards, instant results, permanent record, ability to detect non-metallic materials, ability to estimate depth, ability to see pipes below the floor etc. On the other hand, the principal disadvantage of GPR is that it is severely limited by less-than-ideal environment conditions. Other disadvantages may include: interpretation of radar grams is generally non-intuitive to the novice, considerable expertise is necessary to effectively design and interpret GPR surveys, and relatively high energy consumption can be problematic for extensive field surveys (Russell, 2018).

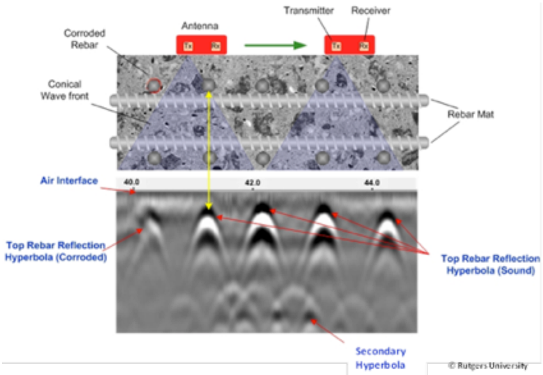


Figure 22 – GPR technique.

2.3.5 Mechanical Properties

Concrete plays a great role in the global stability of the structure. Among its mechanical properties, compressive strength is by far the most important. In general, on-site evaluation of concrete strength is a main challenge in the condition assessment of the existing infrastructure. Many times, managers and engineers prefer to perform non-destructive tests in order to avoid further damage to an already struggled structure.

The most common tests for measuring the mechanical properties of concrete are compression test on concrete cores, pull-off test, rebound hammer, ultrasonic pulse velocity, sample extraction for mechanical testing in laboratory, or combined tests. They are all efficient to evaluate mechanical properties; however, there are pros and cons for each method.

In the compression test on concrete cores, the core of the concrete is taken out of the surface, by cutting and sawing, and the surface is prepared. The advantages are related to the velocity and accuracy of this test; indeed, it is the fastest and most reliable way to evaluate the compressive strength of the concrete. However, this method requires sampling which may affect the reinforcing bars. Thus, rebar locating measurements are needed to avoid this problem. Moreover, it is quite difficult to select the best location for collecting cores if non-destructive techniques for analyzing the internal structure are not available.


Figure 23 – Pull-off test.

The pull-off test (Figure 23) is used in order to determine the adhesion strength between a render and a substrate and is defined as the maximum tensile strength applied by a direct load perpendicular to the surface of a render on a substrate. The adhesive strength is the quotient between the failure load and the tested area. It is a widespread method performed with a pull-off dynamometer specified in several standards (e.g. ASTM C1583). It is an easy test to perform and can be applied onsite, with robust test results. It is a minor destructive technique because the lacunae left can be easily filled in (Lourenço, 2019).

The Rebound test is a non-destructive technique which enables determining the rebound number of hardened concrete using a steel hammer. The information related to the test performance is explained in the international standard *C 805 – 02 Standard Test Method for Rebound Number of Hardened Concrete* and the European standard *(BS EN 12504-2:2012)*. In combination with destructive tests (i.e. compressive tests of specimens), it allows determining the strength of the material and its homogeneity along the structural elements.

The principle behind this test is based on the stroke of a spring-propelled mass to an appropriately prepared surface of the structure or specimen to be tested and the measurement of the rebound distance as an expression of the hardness of the material – the results might be expressed also in terms of energy or differential velocity – after an appropriate correlation related to the instrument features, a measure of the compressive strength can be estimated. In general, it is useful to determine and locate regions of poor material quality or deteriorated concrete. On the one hand, this method is very easy on-site and provides accurate results but, on the other hand, it depends on the surface condition, presence of rebar and sub-surface voids (Hannachi, 2012).

The ultrasonic pulse velocity technique is an effective method to control the quality of concrete structures and to detect damages in structural elements. It is a non-destructive test that consists on the propagation of ultrasonic waves. It uses frequencies between 20 to 150 kHz, whereas the sonic test uses 1 to 10 kHz frequencies. In general, four different kinds of waves are employed: P-waves, S-waves, R-waves and L-waves. Through the direct test, it is possible to estimate the velocity of propagation of P-waves, whereas the semi-direct test gives information regarding S-waves. The combination of the two types of tests allows to calculate the value of the Poisson ratio, consequently, taking into account the value of the mass density, the modulus of elasticity can be obtained. Overall, this method is useful to detect sub-surface deficiencies, but is also affected by rebars, voids and cracks (Hannachi, 2012).

The tensile strength test (Figure 24) is a method that consists of applying a diametric compressive force along the length of a cylindrical concrete specimen at a rate that is within a prescribed range until failure occurs. The resulting orthogonal tensile force makes the specimen fail in tension. The maximum load sustained by the specimen is divided by appropriate geometrical factors to obtain the splitting tensile strength. The splitting tensile strength is used to evaluate the shear resistance provided by concrete and to determine the development length of reinforcement.

The three-point bending flexural test provides values for the modulus of elasticity in bending, flexural stress, flexural strength and the flexural stress/strength response of the material. The main advantage is the ease of the specimen preparation and testing. On the other hand, the disadvantages are the sensitive of the results to specimen and loading geometry and strain rate. With this test, it is possible to get the results of the Poisson coefficient and Young modulus, and the information related to the test can be found in the international standard *(BS EN 12390-6:2009).*

Figure 24 – Tensile strength test.

2.3.6 Transport Properties

It is widely known that the durability of reinforced concrete structures depends on its porous networkwhich determines its transport properties. Therefore, it is important to monitor concrete structures under exposed conditions so that the interior of the material is not affected by deleterious substances (Nanukuttan, 2009).

To monitor transport properties of concrete, two non-destructive tests can be performed in situ: the Autoclam Permeability System and the Permit Ion Migration Test. The first one is able to measure the concrete permeability and the second one aims to determine the ionic transport of concrete (Nanukuttan, 2009).

The moisture content (Figure 25) and pore size distribution are also usually measured. For the characterization of the porous structure, it is important to mention the mercury intrusion porosimetry test and X-ray micro tomography (Hongyan, 2013). The moisture distribution in concrete elements can be determined non-destructively onsite using a microwave-based sensing device. The values obtained should be complemented by the gravimetric determination of the moisture content in collected samples. Indeed, the moisture content intake can affect the reinforcement bars, so it is desirable to keep an efficient monitoring in concrete structures (Marcos, 2016).

Figure 25 – Hygrometers.

2.3.7 Structural Assessment

Structural assessment aims to identify the structural integrity and global stability of structures and their components, respecting the respective building codes. Structural assessment focuses on evaluating how reliable the structure is able to support current and future loads. With this approach, both ultimate and serviceability limit states are analyzed. There are many options to perform efficient structural assessment. Choosing the correct procedure requires a detailed analysis of the actual structural situation of the deteriorated elements (Rohrmann, 2006).

To define the structural condition of a reinforced concrete construction, a structural capacity assessment should be performed. Corrosion and material assessment must also be considered. Some structural assessments may pose difficulties, for instance, in reinforced concrete samples, the estimation of mechanical properties for larger diameter bars is very limited since the relation between the diameter of the thickness and the mechanical properties is inversely proportional (Marcos, 2016).

In general, when performing structural assessment, the analysis is focused on the most deteriorated elements, making sure the state of the concrete and reinforcing bars are well examined. During structural assessment, it is possible to figure damages in the surface (e.g. carbonation and rebar corrosion) and interior (e.g. freeze-thaw cycles and water infiltration) of the concrete.

Among the different methods to perform structural assessment, the most relevant are the methods of data acquisition (e.g. study of documents, inspections, material testing, performance testing and monitoring), methods of structural analysis (e.g. analysis methods and adaptive models), and methods of reliability verification (e.g. deterministic verification with global safety factors, probabilistic verification, target reliability) (Rohrmann, 2006).

2.4 Conservation Techniques

Massive reinforced concrete structures with a significant construction age usually have problems related to concrete properties, affecting performance, durability and stability over time. In many cases, repair is less expensive than reconstruction (Taillet, 2014). Indeed, efficient approaches to the deterioration mechanisms can lead to time/money saving.

Many constructions face deterioration problems and need repair/maintenance. When the damages and their possible causes are correctly analyzed, removal and substitution may not be necessary. Nowadays, more than 300,000 buildings are demolished annually, generating almost 170 million tons of construction and demolition debris. Perhaps, not all of these structures would have needed to be rebuilt if they had got accurate analysis for conservation techniques (Lamore, 2018).

When performing a conservation intervention, the building codes must be respected as well as damage glossaries, since they help guiding which procedure to follow. Some heritage agencies have been working to improve the techniques of conservation and to propose new methods of repairing a structural deterioration. There is also a need of understanding the behavior of historic concrete structures in order to correctly propose recommendations (Macdonald, 2014).

In general, it is necessary to evaluate some factors so that a good approach can be proposed, such as potential background research and other current needs, material properties, most severe deterioration mechanisms and current structural state. Overall, in all kinds of engineering structures, it is important to keep a regular monitoring so that damages can be treated without future complications to the structure.

In order to keep reinforced concrete structures safe from future damages and to solve the actual deterioration mechanisms, some conservation techniques must be performed. Overall, the most relevant conservation techniques for reinforced concrete structures are the removal of damaged concrete and respective replacement, grouting and injections, surface treatments, electrochemical treatments, and strengthening.

2.4.1 Concrete Removal & Replacement

In general, conservation work often aims for replacement of materials, both materially and aesthetically. When a structural element is too damaged to be treated, concrete removal may be required. When a concrete structure is deteriorated, local removals may reveal corrosion damage of reinforcement. This technique may indicate a better way to solve structural problems of corrosion or any inconvenience related to the concrete material. Moreover, the replacement should indicate a good possibility to structurally increase the affected material components (Souponitski, 2001).

Despite these advantages, the removal of concrete in reinforcing steel structure is restricted, which can negatively interfere on the analysis of the interventions that must be made. Indeed, the data collected may be limited, leading to a complex challenge to detect the appropriate procedures (Crevello, 2015).

Moreover, the replacement of concrete structures should guarantee the same material properties. If there is any structural incompatibility, the concrete will be susceptible to suffer new deterioration mechanisms, resulting in an undesirable damage-cycle circumstance. For instance, incompatibility in physical performance especially affects the moisture movement, which can lead to accelerate deterioration of adjacent materials through freeze-thaw cycling and salt crystallization mechanisms (Souponitski, 2001).

Furthermore, new concrete can also have troubles to structurally connect to old concrete. That is why the industry tends to use polymer-modified mortars, but there may be alternatives that should still be investigated and developed before applying in situ (Macdonald, 2014).

Therefore, the understanding of the decay and deterioration mechanisms is vital to secure the increase of conservation skills that are able to prolong the service life of the structures for future generations. Also, engineers must make ensure that the new concrete structure is compatible to the replaced old material in order to avoid worsening the deterioration mechanisms.

2.4.2 Grouting & Injections

In order to treat cracks, a common conservation technique applied is grouting. This method is a process of filling cracks or voids under pressure in concrete or masonry structural elements. It is useful to repair cracks and strengthen the damaged concrete member. The pressure of the jet depends on the area of the structural members. In small sections, for example, the procedure requires gravity or low-pressure grouting, so that the member's properties are not affected (NATIONAL RESEARCH COUNCIL, 1982).

Overall, grouting (Figure 26) represents the injection of a binder filling the voids of the concrete, forming a connection and giving a better cohesion to the mortars and a better adhesion between the masonry or concrete components. Poor results in grouting can be related to the following factors: inhomogeneous strength and stiffness in the injected parts of the walls; poor penetration and diffusion of the new materials due to difficult injectability of the grout itself or due to a poor technique of injection; segregation and shrinkage of the grout due to high absorption of the original materials; and/or possible chemical and physical reaction between the grout and the existing materials (Liu, 2012).

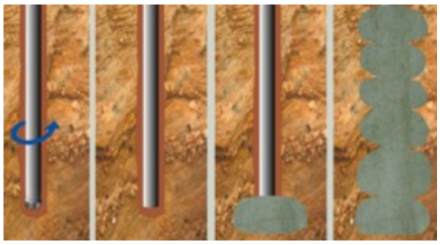


Figure 26 – Injection technique.

A good crack repair technique has been developed in the laboratories of Ghent University, and consists on the use of bacteria that produce urease, catalyzing the hydrolysis of urea (CH_4N_2O) into ammonium and carbonate (CO_3). The calcium carbonate ($CaCO_3$) precipitation was used for consolidation of sand columns, healing of cracks in granite or for surface treatment of limestone (Tittelboom, 2010).

2.4.3 Surface Treatments

In order to prevent and repair surface damage to concrete structures and to provide additional protection for materials against degradation, several approaches can be chosen such as surface coating, hydrophobic impregnation, pore blocking surface treatment and multifunctional surface treatment. These techniques are related to metal, epoxy resin and polymer coatings for steel rebar, corrosion inhibitor, electrochemical method of re-alkalization and concrete surface treatment (Antunes, 2010).

Whenever a structure is exposed to extremely aggressive environments, deterioration and damage mechanisms may occur. Therefore, conservation techniques are more than necessary to keep the structure safe. A great technique that has been increasing over time is the surface treatment that helps extending the service life of the building and increasing structural factors (e.g. permeability, bonding strength and cracking resistance).

However, it is essential to deeply understand the mechanisms of this conservation technique since many researches are still ongoing in order to evaluate all characteristics of the method, especially at micro-scale levels. For instance, the main deterioration processes found on concrete surfaces are related to high concentration of carbon dioxide leading to the formation of black crusts (mostly related to traffic pollution) and, if there no proper investigation studies are performed in advance, the treatments may fail in correctly protecting the structure (Ozga, 2011).

The lack of materials for the conservation of historic concrete has justified the launching of the European project INNOVACONCRETE, which is currently developing innovative materials focused on historic concrete, such as crack-free consolidants, smart nanostructured materials for corrosion inhibition, consolidants with high affinity for carbonate species, long-lasting super hydrophobic products among others.

Overall, one of the most commonly used methods is the organic surface treatment because of their good protective effect. The most common inorganic surface treatment is the sodium silicate (Na_2SiO_3) solution (Antunes, 2010).

2.4.4 Electrochemical Techniques

Many reinforced concrete structures face problems related to carbonation-induced corrosion. One of the most reliable methods to minimize this problem is the electrochemical technique, which presents lots of advantages in preserving carbonated concrete and minimizing alterations of the surface. Thus, this technique is attractive for façades and monuments with high historical, cultural and architectural values (Redaelli, 2011).

Overall, the electrochemical treatment is a non-destructive technique which can be applied in reinforced concrete structures in order to inhibit the corrosion of the reinforcement. It can be applied either on the concrete surface or embedded in the concrete. In order to achieve accurate procedures, the rebar placement must be identified, the corrosion rate must be specified and the concrete resistivity must be measured (NEA/CSNI/R, 2002).

This method has been used for decades, but it is still being tested in laboratories in order to achieve even better results. Indeed, some on-site applications have not been clarified yet. Among these, the most relevant methods are the re-alkalization, chloride extraction and cathodic protection (Redaelli, 2011).

Summarizing, the electrochemical reaction takes place in the presence of an electrolyte, represented by the aqueous solution saturating the concrete pore networking. The formation of cathode and anode may occur in a same metal, due to the presence of impurities, or irregularities that cause differences in the concentration of oxygen in the surface of the metal. The main difference between electrochemical reactions and carbonation is the chloride concentration in solution and not the pH decrease. This leads to the oxidation phenomena in alkaline systems too, typical of sound concretes (Secco, 2019).

Regarding the relation between pitting and trans passivity, the behavior of steel in concrete changes in the presence of chlorides. The electrochemical behavior of steel in concrete is expected to be in passive range; however, if there is a considerable concentration of chlorides, the behavior on the surface of the steel rebar becomes active (Redaelli, 2011).

2.4.5 Strengthening

When a concrete building is structurally damaged or has insufficient load properties, structural strengthening is required by e.g. adding bars of steel, or stirrups to improve the tensile strength, decreasing its chances of deteriorating and getting damaged due to overloads. Strengthening is imperative when concrete structures are no longer considered safe (Jumaat, 2018).

Moreover, the addition of live loads (e.g. dynamic forces) or possible design modifications can also lead to the necessity of strengthening. Indeed, concrete structures are always designed to support certain kinds of loads; if somehow the design perspective is changed, it is natural that the building needs to improve its mechanical properties to prevent collapse.

One of the reasons to apply strengthening is the concrete overlay. The use of stiff concrete in situ often results in an uneven surface of reinforced concrete elements that need subsequent floating with cement mortar, which may lead to a decrease in the compressive strength of protective concrete layers. Improving the concrete properties may lead to a better structural scenario (Souponitski, 2001).

As a method for protection and repair of reinforced concrete structures, strengthening can be done by the following ways: adding or replacing embedded or external reinforcing bars; adding reinforcement anchored in pre-formed or drilled holes; bonding plate reinforcement; adding mortar or concrete; injecting cracks, voids or interstices; filling cracks, voids or interstices; and prestressing, or post tensioning (Heinemann, 2008).

However, the effectiveness of this method depends on the surface preparation and bonding methods between existing concrete and steel plates. In general, the use of steel plate is considered the preferable method due to their advantages (e.g. easy construction work, minimum change in the overall size of the structure after plate bonding and less disruption to traffic while the strengthening work is being carried out). Therefore, it is recommended to secure a correct surface preparation in order to accomplish accurate results after concrete strengthening (Jumaat, 2018).

3. METHODOLOGY

Overall, this thesis was divided in two parts. The first part is related to academic research and background information regarding the state-of-art on concrete materials, damages, monitoring methods and conservation techniques for reinforced concrete structures. The second part describes the case study of this work, the Great Strahov Stadium in Prague, analyzing all its historical and architectural information, as well pointing out the damages and deterioration mechanisms found in situ, with their respective proposals for repair and maintenance.

In order to get more accurate analysis of the studied structure, successful interventions in similar buildings were taken into account. Analyzing similar buildings which have undergone successful conservation/re-adaptation proposals can help in finding a successful strategy for revitalizing the structure addressed in this study.

Due to time and sampling allowance constraints, only a few samples were collected for analysis. The collected samples were fallen/falling from the structure during the first visit to the South wing of the stadium. The following techniques were employed for analyzing the samples collected: Thermogravimetry (TG), Scanning Electron Microscopy (SEM), salt content with Merck stripes and pH measurement.

The few samples analyzed under the mentioned circumstances were meant to provide some insights into the type of materials and their state of conservation and guide in recommendations for future analysis.

3.1 Successful Interventions in Similar Buildings

Even though each building has its own characteristics and has particular behaviors under different conditions, they can be compared and analyzed as a whole, especially buildings with a similar structure. Therefore, when deteriorated concrete buildings receive proper conservation techniques, it is possible to figure how it will behave after repair/maintenance procedures. On the other hand, if a conservation technique was not well implemented, it is also essential to realize the actual possible problems the structure may still have.

Among successful interventions in similar buildings, the cases of the Brazilian stadiums Maracanã, Morumbi and Serra Dourada were taken into account. As Brazil host both the World Cup 2014 and the Olympic Games 2016, many of the stadiums suffered alteration and structural interventions in order to ensure the FIFA and comittee standards. These interventions were analyzed to better support the conservation proposals for Strahov stadium, since these stadiums are all dated from the last century: Maracanã (1950), Morumbi (1953) and Serra Dourada (1975).

3.2 Archive Research

Throughout this thesis, many references were used. Books, journals, magazines and articles were studied in order to improve the reliability of the results.The deterioration mechanisms, monitoring and conservation techniques were reviewed to suport the current study.

3.3 Sampling and Methods of Analysis

The first access to the South tribune (Figure 27) of the stadium occurred under the program of Open House Prague, an event which fosters the appreciation of buildings of architectural interest which are not open to the public. As mentioned, one of the objectives of this thesis was to make a proposal for further analysis and general conservation approaches, but this occasion emerged as an opportunity to collect a few samples which had fallen dawn from the structure for assessing the type of materials and their state of conservation.

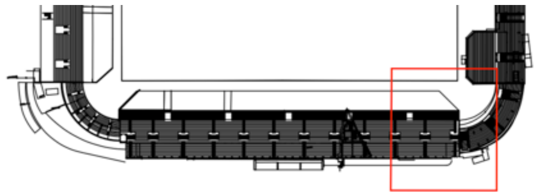


Figure 27 – South tribune access.

3.3.1 Scanning Electron Microscopic Analysis (SEM Analysis)

Before performing this test, the cross-sections of the samples were prepared by impregnating them with epoxy resin followed by drying at 60°C and then polishing. Afterwards, the specimens were coated with a thin layer of carbon and analysed with the scanning electron microscope (SEM) MIRA II LMU (Tescan) equipped with energy dispersive X-ray detector (EDX) from Bruker Corporation. The images were collected under high voltage (15 kV) at a working distance of 15 mm and under high vacuum regime.

3.3.2 Binocular Microscopy

In order to perform the binocular microscopy analysis, the samples were placed below the hand-held binoculars, which range from small 3x10 Galilean opera glasses. The photos were taken via a computer connected to the microscope.

3.3.3 Thermogravimetric Analysis

Small pieces of the mortars were gently crushed in a porcelain mortar and the fractions with grains under 0.063 mm were used for thermal analysis. Then, the thermal analysis was performed with instrument Discovery SDT Q650 (TA Instruments). Samples were heated in nitrogen atmosphere in alumina cups up to a temperature of 1000°C at a rate of 20°C/min to obtain the TGA/DTG (thermogravimetric/derivative thermogravimetric analysis) traces.

3.3.4 Salt Content

The samples collected were analyzed using semi-quantative chemical stripes (Merck) for assessing their soluble salt content. The following analyses were performed according to the manufacturers' procedure: chloride (Cl^{-}), sulphate (SO_4^{-2}), and nitrates (NO32- and NO2-). The pH level from the solutions prepared for soluble salt content were also analysed with pH stripes. However, the tests revealed no salt content. The obtained values were very close to zero. This may be due to the fact that the test has a low precision, so their type of chemical analysis should be performed in order to ascertain the salt content of the material, as well as ion chromatography, X-ray diffraction and so forth. The test was performed according to the correct procedures, by weighting the exact quantities of specimen and water (balance – Figure 28), and some results were even replicated in the following days, but they persisted to present null values of salt content.

Figure 28 – Balance.

In general, the solutions were prepared in advance: 1.0g of material (limestone) was mixed in 100ml of water and periodically mixed for 24h. Then, it was filtered and the soluble fraction of the solution was ready to analyse. The conductivity and pH is simply measured with a conductimeter device. For the semi-quantitative analysis oof the anions paper stripes (Quantofix Macherey-Nagel) are used to quantify nitrates, sulfates and chlorides content.

4. CASE STUDY: STRAHOV STADIUM

This thesis was focused on a reinforced concrete structure built in the 20th century. The selected structure was the Great Strahov Stadium, located in Prague, Czech Republic. It is one of the largest stadiums in the world. Currently, the construction is structurally damaged and, in some areas, the concrete requires urgent intervention. The South and North tribunes of the stadium are in a derelict state. In general, the stadium itself represents an Atlas of concrete damage, since it shows the most typical types of concrete damage

In order to propose efficient conservation techniques, the stadium was studied in all its aspects, including historical background (e.g. social and political context, construction history, local setting and past interventions), social relevance, architectural information, material compounds, building techniques, damage mapping, deterioration mechanisms and their possible causes. Conservation techniques were proposed aiming not to affect the original structure and materials, just like it is required for ancient buildings.

Recently, several political efforts and dissertations have been proposed for revitalizing the stadium, trying to find a new use for it.

4.1 Historical Background

The Great Strahov Stadium (Figure 29) is one of the most notable concrete structures in Prague. With a capacity of 250,000 spectators, it was built in to host synchronized gymnastics on a massive scale. The structure covers an area three times longer and three times wider than a standard soccer field. It is the largest stadium and the second largest sports venue ever built. The construction began in 1926 and the largest attendance was recorded in 1938 on the occasion of the jubilee “World Anti-War”. In 2003, it was classified as a public interest heritage (nemovitá kulturní památka).

Figure 29 – Strahov stadium.

Throughout the years, the venue was the stage of great social events, such as American football matches between army units, music performances, motor racings and so forth. In the 1990s, for example, the venue hosted more than ten concerts, with over 100,000 people.

Overall, the stadium was a place with lots of admiration by society and had lots of use in the last century. According to the plans from 1913, the stadium was expected to be even larger, because it was supposed to continue up to Ladronka, an area nearby the complex.

Despite its importance during the last decades, the stadium is no longer in use for competitive sports events. Important to notice that the stadium is so big because it was built to host mass synchronized gymnastic events e.g. Spartakiadas. The Strahov Stadium is collecting more financial losses than profits, as many other big stadiums (e.g. the African stadiums after World Cup 2010). It is still requiring money for maintenance and the economic return is not being worth it. In general, the structure is only being used as the training center for the Athletic Club Sparta Prague (the biggest and most known soccer team in Czech Republic), as soccer training for youth.

During the first decades of the 20th century, the districts of Prague were fighting each other to host big events such as the Sokol festivals, which were always a major event for the entire Czech Republic community. After World War I, the capital city of Prague bought the land at Strahov and made plans for their landscaping and communication. At that time, there were only dense inaccessible forests and a quarry. So as to help with the demanding preparations, the city had a state that had acquired the building rights for it for 80 years, and had built its own utilities and landscaping on their own.

Despite all the efforts to keep Strahov as the main host for festivals, the VII Sokol festival in 1920 was held in Letná, another area in Prague. In 1925, the Ministry of Public Works officially authorized the work in Strahov. Thanks to his efforts, the VIII Sokol festival it was held in Strahov in 1926. The area and program corresponded to the present form, but it was still a provisional structure. The Eastern tribune with the men's gates and the Western tribune with the presidential gates were made of wood. The North and South Tribunes stood on earthen ramparts. Figure 30 illustrates the North tribune during that period of the communist era (Rostislav, 2012).

Figure 30 – North tribune in 1950s.

In general, all concerts and festivals totallized, together, over 133,000 spectators. The whole area occupied 600,000 square meters, of which 46,000 square meters were built directly on the ground. In the end of the 1920s, the Masaryk State Stadium, the so-called Strahov Stadium, was being discussed for the first time. In 1930, an event was organized in the stadium, counting with a rink, an Athletics track, a football stadium and a troop training area. Figure 31 represents a festival held in 1932.

Figure 31 – Strahov stadium in 1932.

Overall, studying the historical background (e.g. social and political context, construction history, local setting and past interventions) of the stadium allows getting better knowledge on their actual condition. As this structure has been built almost 100 years ago, it is essential to chronologic organize information in order not to get loss.

4.1.1 Social and Political Context

The original stadium dates from the First Republic between the First and Second World Wars. Already in 1926, for the first time ever, an all-Sokol event was held in the Stadium. The idea to locate a new Sokol event center at Strahov came at the initiative of the Czech Sokol community in 1913. In that time, the local lands belonged to the army as part of the Prague fortifications, and the cultural potential of the area turned the place into a sports venue.

However, their efforts were interrupted by the First World War and, in 1919, the Prague City Hall bought the land. In 1925, the army lent the building law to the Czechoslovak state for 80 years. The resulting construction boom led to an increase of industrial buildings, factories, and monuments from this period in Prague and the rest of the Czech Republic. Some of them have been reconstructed and others remain as they were. In this scenario, the Strahov Stadium was one of the most important venues during the Communist era.

During this period, life in the existing Czechoslovakia was completely different. Prague, as the capital, was the seat of the Communist party, whose political decisions were influenced by the Soviet Union. With a dictatorial government, social and economic freedoms were quite hard to obtain and good employments were not easy because the economy was still affected by the wars. The political tension was still hovering in the air for possible new conflicts.

Overall, the stadium was built in a turbulent period since many countries were still recovering from the economic and structural losses caused by the First World War. Some dictatorial governors emerged, increasing the threat of communism, fascism, Nazism and socialism, sometimes breaking the development of new civil engineering structures.

In general, it was a scenario with micro and macro problems. In micro scale, the uncertainty to get good jobs and humanly sustain a family was even bigger, and the unemployment was increasing over time. In macro scale, countries were facing troubles in raising funds to improve the economy.

4.1.2 Construction History

The stadium was firstly built by the architect Alois Dryák, on a wooden structure in 1926, to host the synchronized gymnastic events, such as the Spartakiadas. This construction was preceded by the VIII Prague Heritage Assembly, in 1926, that was already held at Strahov. Throughout the following decades, the stadium was expanded and new construction took place. The first one was related to the structure, when the wooden structure was replaced by concrete grandstands in 1932.

In 1933-1934, the architects Ferdinand Balcárek and Karel Kopp built the track and field stadium based on their design (remodeled in 1978), and added a Western tribune connected to the assembly stadium by quarter-circle connecting segments, accentuated by 28-meter-tall towers for reporters; they also added the Eastern tribune (1934-1935), which was already functionalist in style. The architects placed a broadcasting hall for live music above the gate, so that music could be transmitted to the exercise grounds. All the load-bearing constructions of the tribunes were made from reinforced concrete, with brick fillings (Rostislav, 2012).

During construction, the requirements concerning the different purposes to be served by the complex kept increasing: the Sokol organization demanded the Tyrs Institute for Physical Education become a part of it. Under pressure from the state, the Sokol organization and sports clubs, with the so-called 1935-zoning plan, newly featured swimming and cycling stadiums, tennis courts and children's or Scout playgrounds. Under supervision of the Tyrs Institute, a gymnasium with an integrated lecture hall and adjacent caretaker's apartment was built by 1938. The very first idea for the placement of the rink came in 1913, when the engineer Ludvík Čížek created the concept of a large folk park, which included a sports stadium, grass areas and, in addition to the events, also for military parades. The main impetus was the financial and time-consuming nature of temporary sites, which had been built on Letna Plain for the last few years.

At the beginning of the 21st century, the stadium was close to being demolished. In 2003, part of the stadium, with the financial support of the City of Prague, was built by AC Sparta Prague. Eight football fields arose there and it is now used as a training center for Sparta, as seen in Figure 32. In 2014, the complicated property relations of the stadium were resolved and it is now owned by the city. Both Northern and Eastern tribunes were completed in 1948, but the work itself actually began in 1938. The authors of these tribune constructions were also Balcárek and Kopp (Rostislav, 2012).

Figure 32 – Strahov stadium in 2003.

Moreover, the last Eastern tribune, built by Honke-Houfka, Kuna and Slupka, is the only part of the stadium with an architectural style of the 1970s and 1980s. This fact overshadows both its architectural qualities and the fact that it carries several original independent user functions and is therefore operationally interesting. Indeed, the Eastern tribune was demolished and a new one was built in the end of 1960s and beginning of 1970s (Rostislav, 2012).

The construction of the North tribune began in 1938 and ended in 1948, as well as the South tribune. The West tribune began in 1932 and finished in 1934, and the last construction East tribune started in 1969, finishing in 1972. It is important to mention that both North and South tribunes had two different construction periods. The first one was from 1938 to 1939, and the second one was from 1948 to 1949. The break between the two periods was necessary due to the ongoing Second World War. Below, Table 1 summarizes the initial and final construction dates of the actual tribunes.

Table 1 – Construction period of the tribunes.

Tribune	Construction Period	
	From	To
North	1938	1948
South	1938	1948
West	1932	1934
East	1969	1972

4.1.3 Local Setting

Located in the Strahov district of Prague, Czech Republic, the stadium is surrounded by parks and lakes. It is sited on Petrín hill overlooking the old city, and can be accessed by buses, or by walking from the Malovanka tram station. Prague 6, as the district is officially called, is one of the most expensive places in terms of rental prices.

The tourism in this region is relevant due to its proximity to the city center, as well as to other touristic places such as the Prague Castle and the Monastery. Therefore, there is always a significant traffic of people in the nearby areas, which would be a significant economic advantage if the stadium were in good conditions to still receive tourists and events. Figure 33 represents the city map of Prague, highlighting the Strahov district, where the stadium is located.

Figure 33 – Strahov district.

With its topography and historical development, the Strahov area is has a certain degree of isolation. It has the power and location of a metropolitan peninsula flowing through parks and a tradition of beauty within the urban scenario. Figure 34 illustrates the stadium location over the city map of Prague. The choice of the location construction has a more prosaic cause. Since Prague is located in a place where the wind blows mostly to the East, the building was for the sanitary reasons defined just in the West, so that the smog from the city, where at that time, mainly coal, would flow to the opposite direction. Moreover, the location on the hill is visually attractive due to the impressive view of the entire city.

Figure 34 – Stadium location.

Next to the stadium, there are the Strahov dormitories of the Czech Technical University (CVUT), a great complex of dorms and sports courts. Figure 35 illustrates the Strahov dormitories, which are connected to the CVUT by direct bus lines. The presence of these dorms elevate the flow of people near the stadium, specially during the University sports competitions.

Figure 35 – Strahov dorms.

4.1.4 Past Interventions

In 1930, a public competition for alterations of Strahov for physical education purposes took place. In 1931-1932, the tribunes and embankment slopes were modified, and the central part of the Western tribune was built according to the architectural projects of Alois Dryák. Both selected projects were based on the spatial solution of Ludvík Čížek. After Dryák's death in 1932, the planning work was finally entrusted to Ferdinand Balcárek and Karel Kopp. During Dryák's lifetime and according to his classicist design, the Western reinforced concrete tribune with the presidential bed and the modification of the side embankment tribunes was realized. Figure 36 illustrates a photo of the stadium in 1926.

Figure 36 – Strahov stadium in 1926.

After the Second World War, Spartakiads events started officially taking place in Prague. During its first edition, in 1955, the capacity of the tribunes was increased by the superstructure and the unified frontage in the spirit of Classicism, by the architect Jiří Kroha. Their influence was not limited to the stadium itself. According to their design, the adjacent glass visitor pavilions were built on the northern grounds in the spirit of the Brussels style (Rostislav, 2012).

In the 1960s and 1970s, wooden changing rooms in the Eastern tribune were replaced by today's college dormitories, which continued to serve as changing rooms during the Spartakiads events. Overall, the last major intervention happened between 1962 and 1975, then the Eastern tribune was demolished and replaced by a modern and multifunctional one, with gyms and a swimming pool. The authors were a team of architects composed of Olivier Honke-Houfek, Zdeněk Kuna and Zdeněk Stupka.

In the last decade, several studies have looked at adaptive reuse of this unique structure (e.g. Hroncekova in 2018, Mikulecká in 2009, among others). There are plans to convert the stadium complex into a commercial zone with hotels, restaurants and shopping centers. Another suggestion was to convert the area into a modern leisure venue. There were plans to rebuild the area as an Olympic village if Prague won a future Olympic bid (Rostislav, 2012).

4.2 Social Relevance

Few buildings have had so much importance for society as Strahov Stadium did. It happened not only because of its architectural qualities, the well-known names of its creators, the uniqueness of the place, nor the historical interconnection with the past, but also because it was the host of the Sokol Festival. In 2016, exactly 90 years after the VIII Sokol festival, which was the first one to be held on the site of today's stadium, a celebration was held in the venue. However, the time of greatest fame is over and its future is still uncertain.

Overall, the Strahov Stadium contemplates a wide range of social interests. Throughout the years, the stadium hosted lots of events and played a great role in the economic scenario of the city by the cash flow from these events. Nearby the structure, as already mentioned, there are important points such as the CVUT Strahov dormitories, which were built to support the Spartakiadas events.

The Strahov stadium served as its original purpose practically until the last VI Spartakiad in 1985. Although it was still held a meeting of practitioners (e.g. in 1990 under the name of Prague Sports Games), public interest gradually disappeared. In 1994, a renewed XII Sokol festival took place in the stadium, but the area was already visually diminished and the Northern tribune was no longer used (Rostislav, 2012).

In the 1990s, it was the place of big concerts; however, the intense and sporadic use had a devastating effect on the structure. While the stadium was regularly maintained and repaired in sports games, after 1989 the monitoring mechanisms began to decrease yearly.

Overall, the stadium seems to be facing a better future, thanks to the agreement between the capital city, the Union of Sports and the Football Association of October 2014. According to this agreement, the whole Strahov Stadium and the lands were transferred to the ownership of Prague. The Football Association has won the adjacent Athletic Rošice Stadium and built the Sports House in the complex.

The Athletic Rošice Stadium is the stadium connected by a suspense bridge with the Western tribune of the Strahov stadium, as shown in Figure 37.

Figure 37 – Suspense bridge.

In 2003, the stadium was listed as a public interest heritage, which resulted in increased demands on its handling by the owner. Thus, the structure became virtually conserved and the question of its further use is still crucial. Opinions range from repairing the damages keeping the stadium originality to demolishing the whole structure and readapting. Figure 38 shows the Athletic Rošice Stadium.

Figure 38 – Athletic Rošice Stadium.

4.3 Area of Study

The South tribune is quite similar to the North tribune, while the West tribune has significant differences with the East tribune (both structural and architectural differences). Due to the limitation of time, it was not possible to analyze all four concrete structures of the stadium separately, so only the South and North tribunes were chosen for the work. Figure 39 shows the structure of the chosen North and South tribunes.

The deterioration mechanisms and conservation techniques studied in the stadium refer to North and South tribunes. In South tribune, just a section was analyzed. They can be extended to both West and East tribunes if further material analysis is performed.

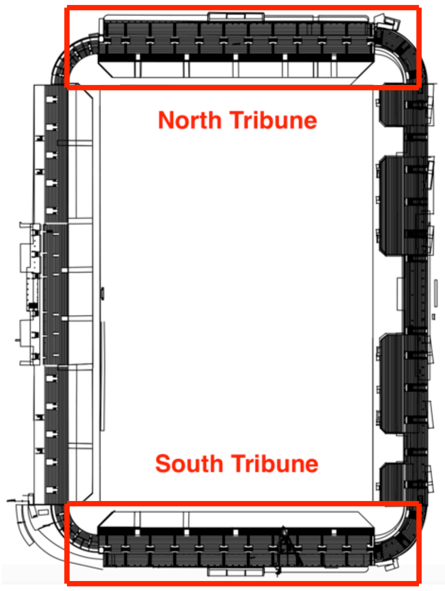


Figure 39 – Area of study: North and South tribunes.

Overall, the North, West and South tribunes are structures from the 1930s years, while the East wing is a concrete structure from the 1970s. As both North and South tribunes have the same structure and are symmetric, the analysis regarding the North tribune can be partially extended to the South tribune; both structures were built in the 1930s but the North tribune is more damaged than the South.

4.4 Architectural Information

The architectural designs are described in this section. Due to the size of the projects, they will be shown in the Annexes.

The samples collected in South tribune can also be analyzed for the North structure, since they were built in the same time with the same techniques. Figure 40 illustrates the front façade of the South tribune, and Figure 41 shows the façade of the North tribune.

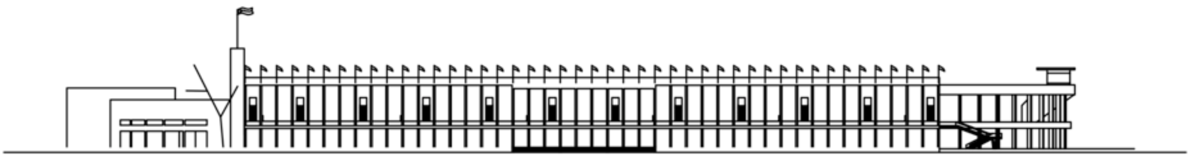


Figure 40 – South tribune: front façade (Stodola, 2016).

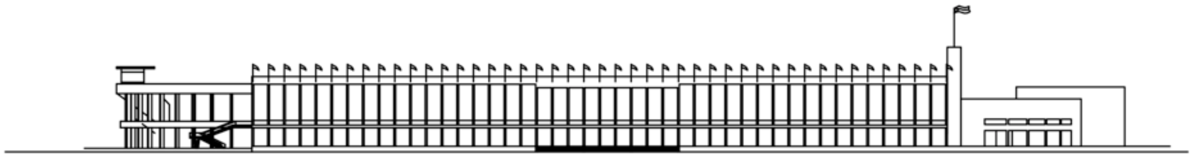


Figure 41 – North tribune: front façade (Stodola, 2016).

The North tribune structure has a total length of 240m, and height of 20m. In total, there are 53 columns, equally spaced (4 m), with an entrance between the 18th and 27th columns. Most of these columns are deteriorated and severely damaged. In the left corner of the North tribune, there is a tower with 28.5 m height and 4 m width, which connects the North tribune to the East tribune. Also, there are two corridors where the audience used to circulate during the events (the first one is 5.3m high, and the second one is 10.5m high), and two stairs, both on the corners of the façade.

The South tribune contains the same measurements regarding length and height. The tower, connecting South and East tribunes, has also the same dimensions of the North-East tower. The number of columns, location of the stairs and dimensions of the columns are all the same as the North tribune. Some plans of the North tribune are presented below.

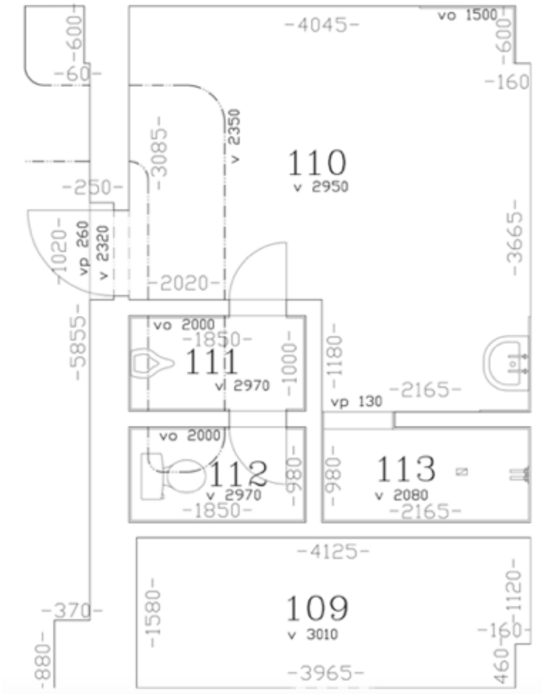


Figure 42 – Bathrooms in the middle side of the North tribune (Stodola, 2016).

Overall, the architecture of the ground floor and first floor are identical. The mezzanine has some differences regarding the size of the bathrooms (Figure 42) but nothing special. Since the left and right structures of the North tribune are mirrored, the same architecture for bathrooms can be seen in both sides. The structure in the middle of the tribune, presenting the stairs to the mezzanine, is shown in Figure 43.

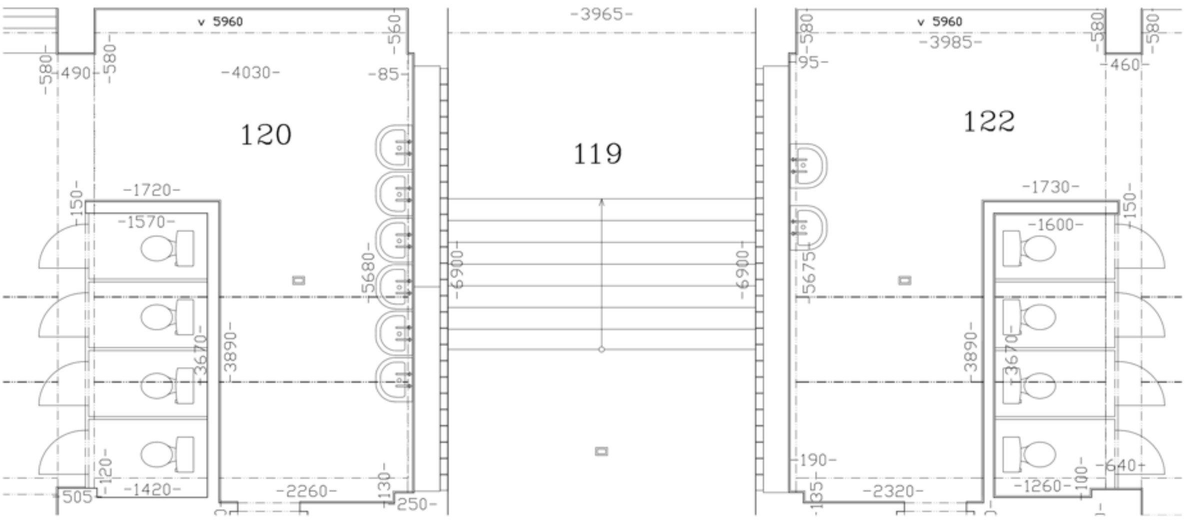


Figure 43 – Bathrooms and stairs in the middle side of the North tribune (Stodola, 2016).

Figure 44 illustrates the architecture of the mezzanine in the North tribune showing the climb of the stairs to the first floor and some bathrooms in the left. Again, as the structure is mirrored, the same architecture can be found in the right side of the tribune.

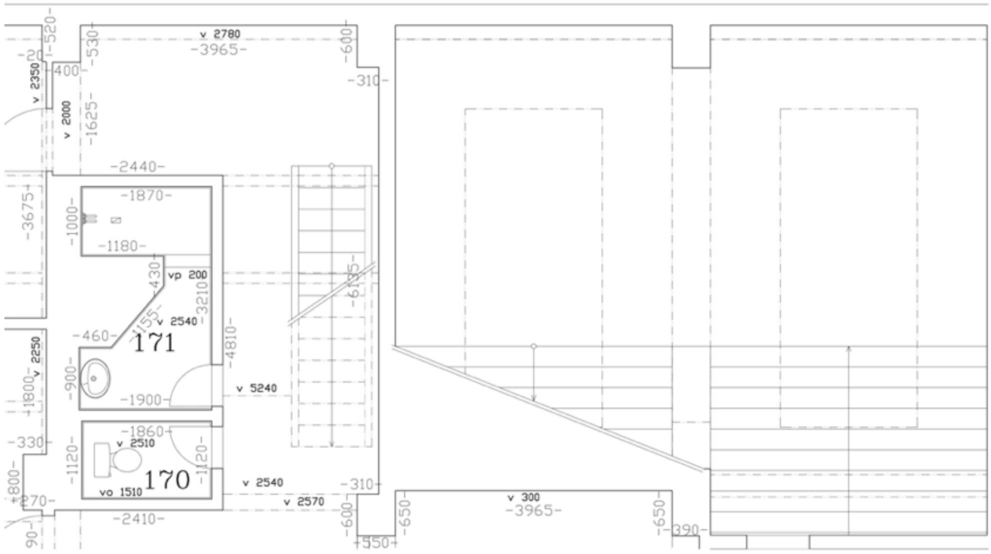


Figure 44 – Bathrooms and stairs in the middle side of the North tribune (Stodola, 2016).

4.5 Building Techniques

The stadium was built through cast-in-place procedures. The cast-in-place concrete, also known as poured-in-place, is a concreting technique that is produced in situ or in the concrete component's finished position. Cast-in-place concrete is usually the preferred choice when building concrete slabs and foundations, as well as components such as beams, columns, walls, roofs, and so forth.

The advantages of implementing a cast-in-place technique are the related to the construction time, since it is perhaps the fastest and most versatile procedure to build a structure. However, it requires a higher number of employees compared to the precast technique. In Figure 45, the cross sectional area of the tribunes are schematically and chronologically organized so as to identify the procedures used to build the tribunes of the stadium

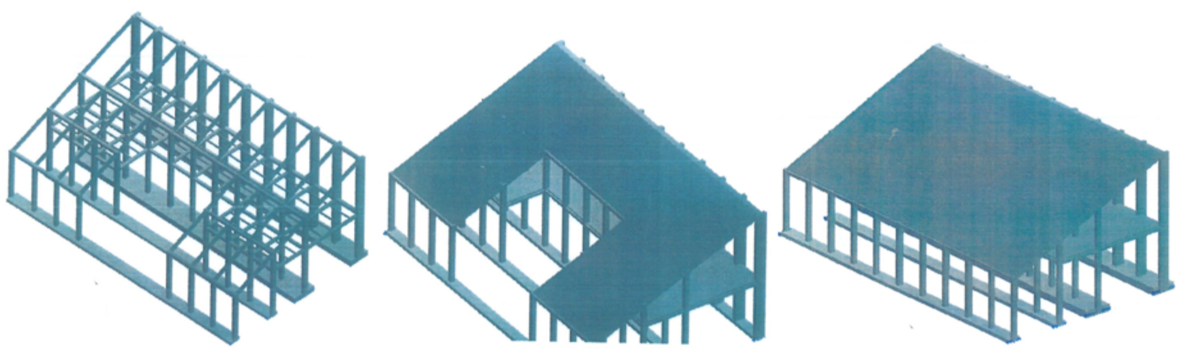


Figure 45 – Construction stages of the tribune (Bittnar, 2004).

Overall, the procedures done in this stadium are the same as all other reinforced concrete structures. The grandstands are types of structures designed to provide step seating and are available in various sizes and configurations. They can be classified as permanent or stationary. Typically large, they are units that will remain in the same location during the construction period, so they are normally anchored to the ground and constructed with light materials.

In general, the grandstands are composed by footrest, seats, steps and guardrails, commonly known as banisters. Used for safety reasons, handrails provide more stability as people enter and exit the bleachers. They should be lightweight for ease of assembly and disassembly, yet strong enough to provide adequate support. Handrails or guardrails shall extend one meter above the lower surface of the access step of the components of the stands (footrests, seats, aisle).

Models were computationally tested and the values of deflection in the structure of the tribunes can be seen in Figure 46. Excessive deflection, above those specified in design, can cause the displacement of floors and the need for structural reinforcement.

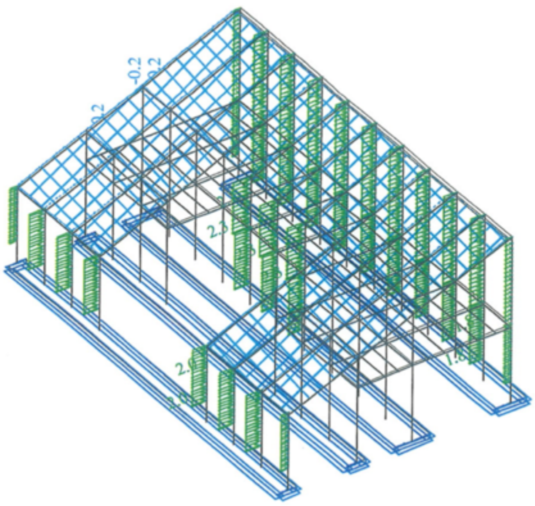
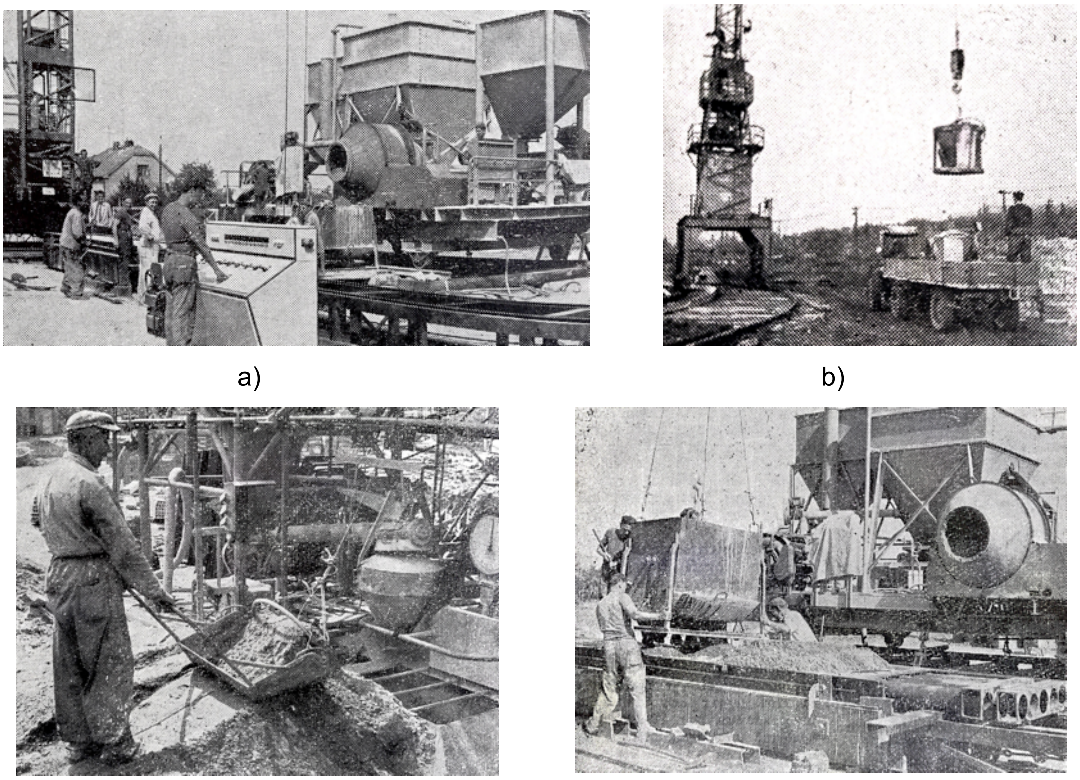


Figure 46 – Deflection values of the tribune (Bittnar, 2004).

As analyzed in the graphical drawing, the biggest deflections (2.3 cm) are seen on the columns in the middle of the structure (in green), while the smallest ones (0.2 cm) are seen in the borders of the structure (in blue). This may be explained due to the high presence of loads in the center or the distance from the supports, turning the area more prone to deflection. Figure 47 illustrates the cast-in-place technique in 20th century: 47a shows the processing of the concrete, 47b is the material transport, 47c is the concrete handling and 47d is the concrete application.



a) b)

c) d)

Figure 47 – Cast-in-place technique (Havelka, 1962).

4.6 Materials

In order to analyze the samples collected in situ and collect the properties of the materials, some tests were performed in the laboratory and are described below. The performed tests were scanning electron microscopy, binocular microscope, thermogravimetry, and salt content. They were all performed in five different samples collected in the corner between South and East tribunes. By analyzing the deteriorated concrete samples under the scanning electron microscope (SEM), it was possible to figure the components of the concrete materials of the analyzed structure. Five samples that were falling/ had fallen from the structure were collected and analyzed. They came from the South tribune, close to the corner between South and East tribunes. Figure 48 represents the location where the deteriorated concrete samples were collected.

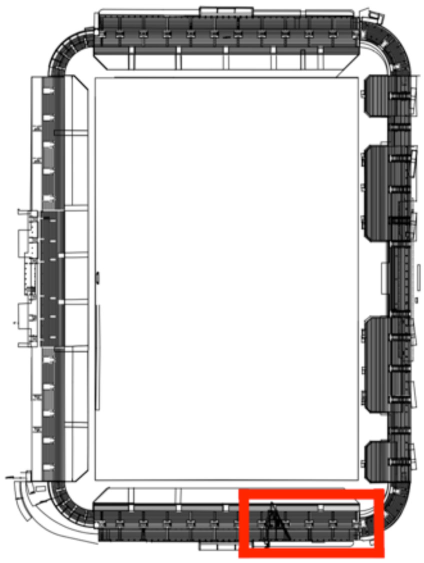


Figure 48 – Samples location.

In this section, the results of the aforementioned tests are analyzed, describing the photos, graphs and data obtained throughout the tests. Samples ST1 and ST2 were collected on the wall of the corredor that gives access to the tribune (Figure 49). Sample ST1 around 1 m high, and sample ST2 around 20 cm high, both on the same wall.

Figure 49 – Location of the ST1 and ST2 samples.

Sample ST3 was collected on the wall of the tribune, close to the grandstands, as shown in Figure 50. Samples ST4 and ST5 were also collected in this same grandstand.

Figure 50 – Location of the ST3 sample.

The following pictures represent the materials collected in situ. Samples ST1 and ST5 represent the mortar of the South tribune, while samples ST2 and ST3 are the concrete and sample ST4 is the pavement of the grandstand.

Figure 51 shows the ST1 sample, which is part of the mortar, has no structural cohesion, being no longer bound. The deterioration mechansisms can be related to crumbling, dusting or disintegration, common processes in the wall where the sample was collected. These damages were probably due to low cement content.

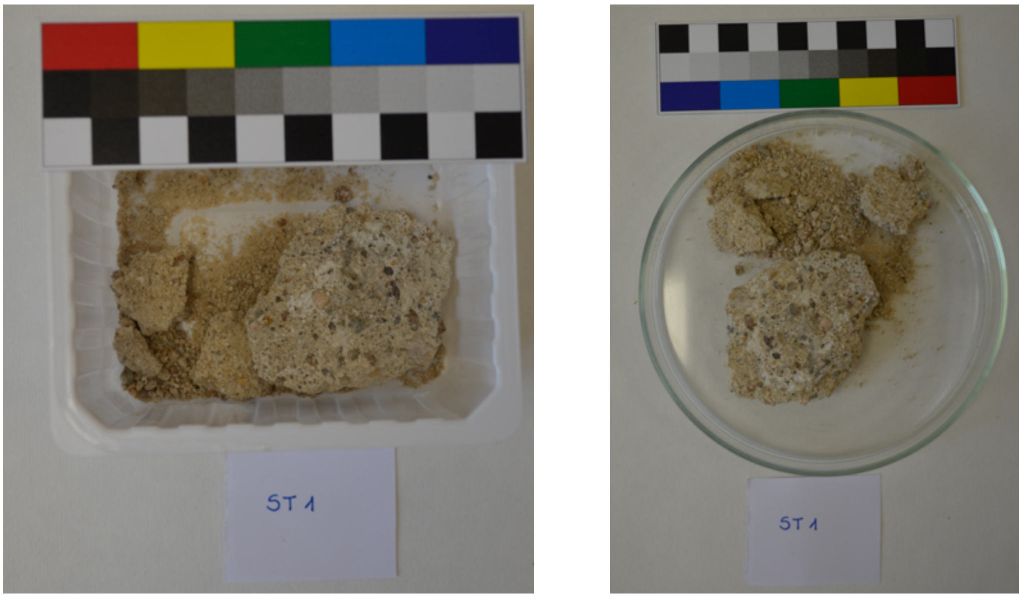


Figure 51 – Sample ST1.

Figure 52 illustrates the ST2 sample, a piece of the structural concrete that also presents loss of cohesion, with signs of crumbling, perhaps because of freeze-thaw cycles.

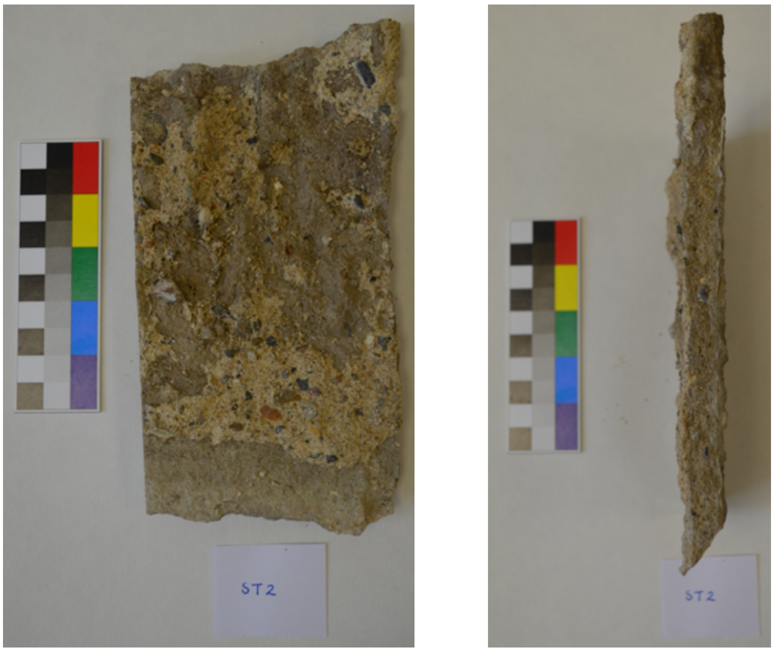


Figure 52 – Sample ST2.

Figure 53 shows the ST3 sample, also a specimen of the structural concrete, that suffered loss of cohesion by disintegration processes maybe due to the surface exposion. As it is part of a wall exposed to pollutants, the acidic attacks are more prone to occur.

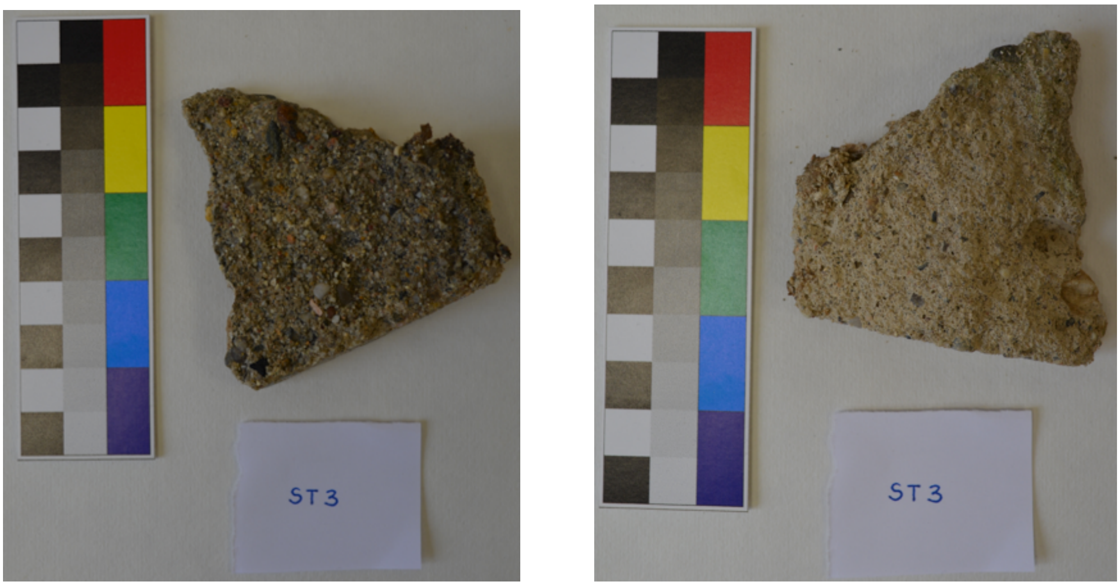


Figure 53 – Sample ST3.

Figure 54 illustrates the ST4 sample, originated from the paviment. The specimen contains small cracks on the surface. Since it was collected from the ground of the grandstands, the causes for these cracks may have been mechanical impact, overloading or even thermal stresses.

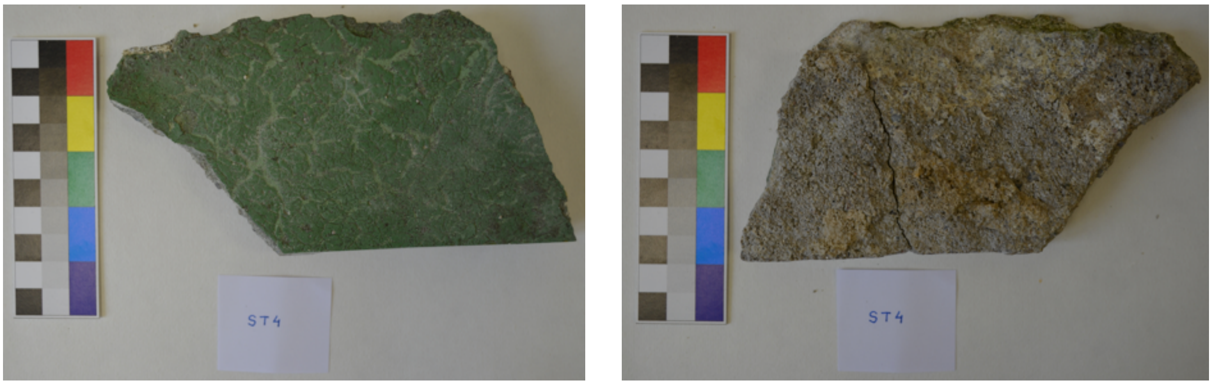


Figure 54 – Sample ST4.

Figure 55 shows the ST5 sample, which is also part of the mortar with no structural cohesion. The specimen contains signs of both crumbling (maybe due to low cement content) and erosion (perhaps due to external action).

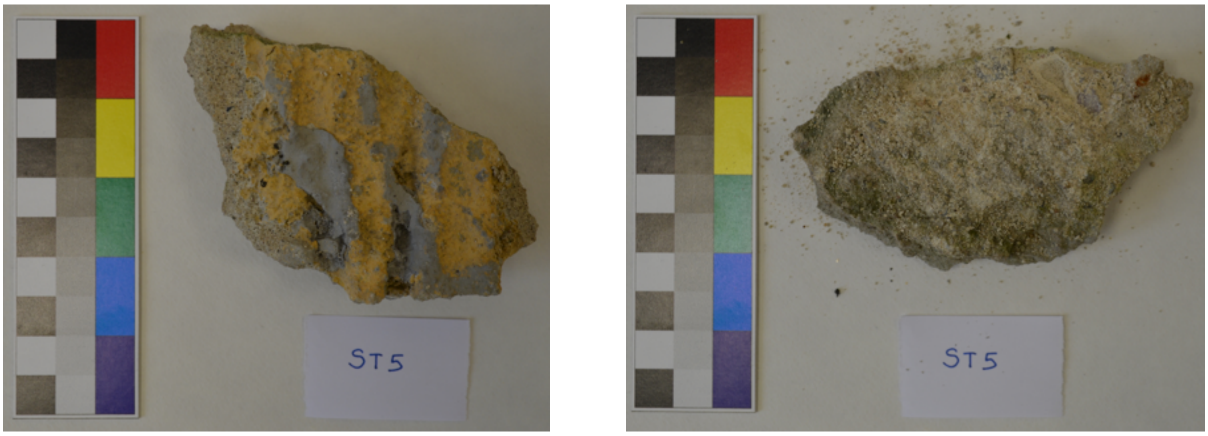


Figure 55 – Sample ST5.

4.6.1 Microscopy

Micrometric analysis of hardened concrete may be used to determine the content of binder and aggregate. It is a suitable alternative to chemical analysis methods for determining cement content and aggregate grading. To perform the microscopy analysis, two different tests were performed with the concrete samples: the binocular microscope and the scanning electron microscopy. Both were useful for the interpretation of the characteristics of the samples and are described below.

4.6.1.1 Binocular Microscopy

The volume proportion of aggregate, cement matrix and air voids are determined by using a binocular microscope with the aid of an oblique incident light. Figure 56 shows the results for sample ST1, exhibiting some cracks with rust deposits. It is possible to see some damages in the structure (e.g. thin interconnected cracks on the surface maybe due to exposure to high temperatures or overloading).

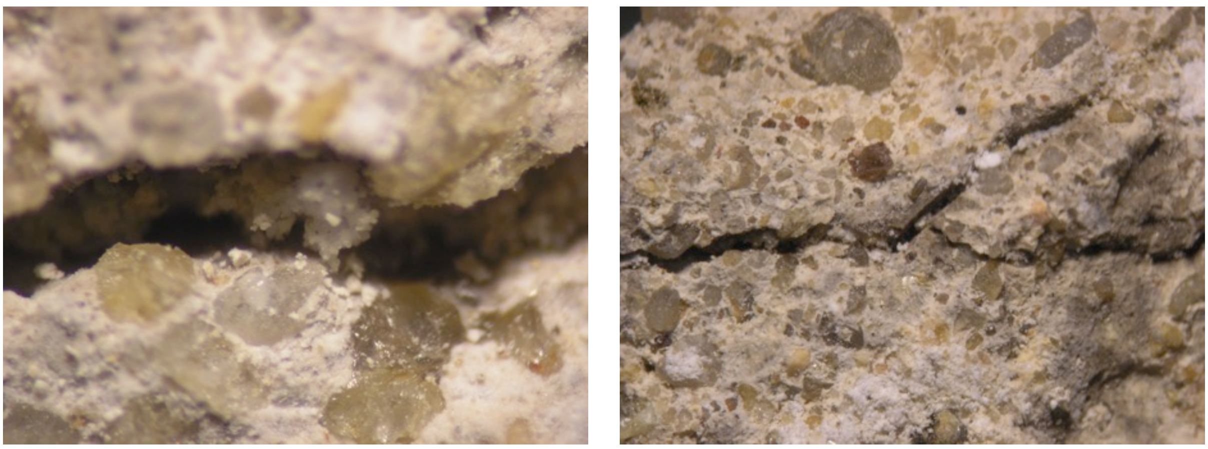


Figure 56 – Sample ST1.

Figure 57 shows the results for ST2. It is possible to see the peeling of the paint, probably due to oxidation or high temperature.

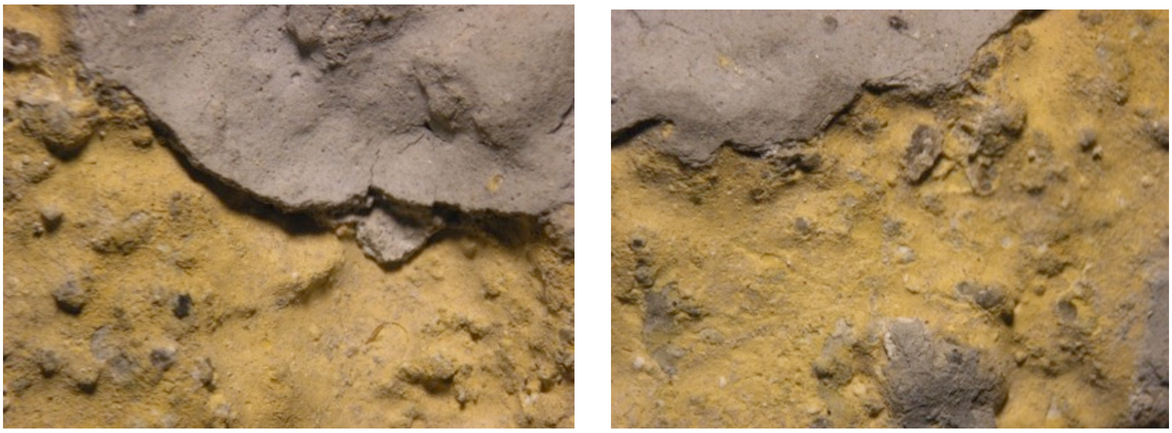


Figure 57 – Sample ST2.

Figure 58 reveals the particles of the ST3 sample, indicating different minerals (as explained in the following sections, the lighter particles indicate the presence of aluminium and iron, and the darker particles reveal the high content of silicium). Also possible to see that there are some disintegration (pop-outs) maybe due to a disruption of the aggregate.

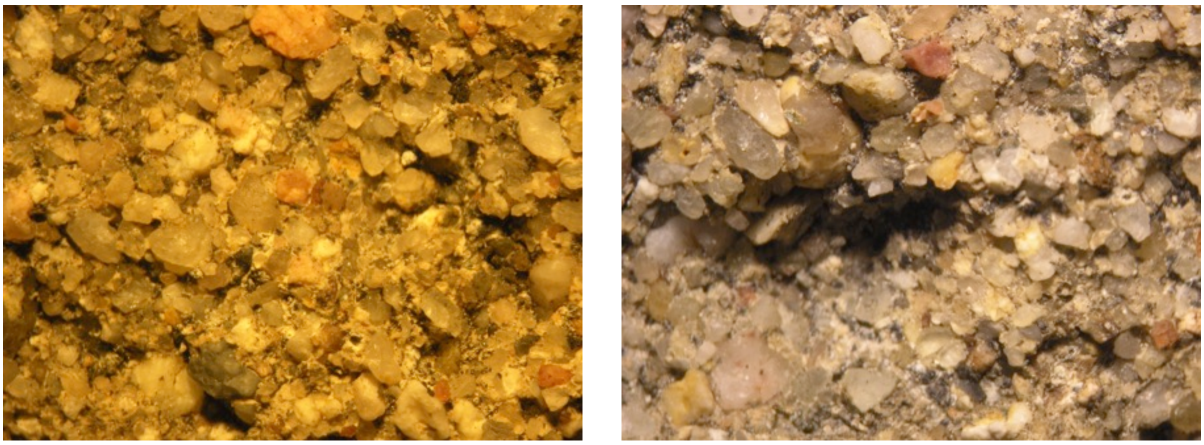


Figure 58 – Sample ST3.

4.6.1.2 Scannig Electron Microscopy (SEM)

The scanning electron microscope provided analysis that show the differnet chemical compositions of the samples. By analyzing the percentage of the compounds, it was possible to determine the type of concrete on the specimens and, consequently, the type of material in the region where the samples were collected. As there are many different compounds in the samples, the analysis were divided into different regions so that the elementary averages could not be affected by different grains. In general, they were divided in areas with high content of calcium oxide (CaO), silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and so forth.

The ST2 sample is shown in Figure 59, where it is shown in its integrity. As in the other specimens, the grains vary in sizes and components, so there is no way to collect one unique average for the whole specimen. The first photos provided by the SEM indicate the presence of different chemical compounds (e.g. red for calcium, green for silicon, blue for aluminium, pink for iron, yellow for sulfur and so on).

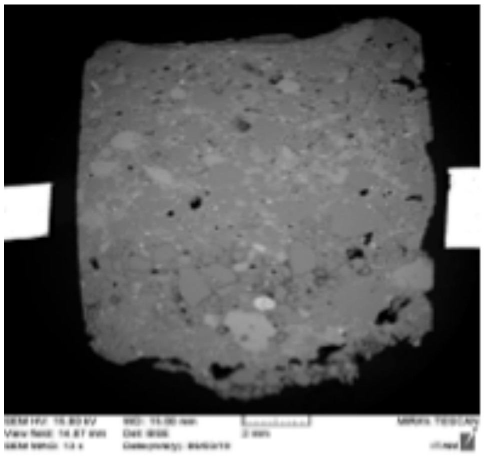
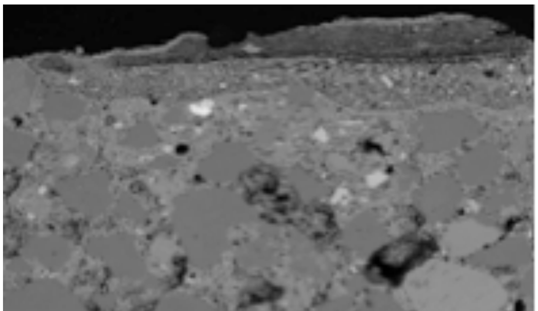
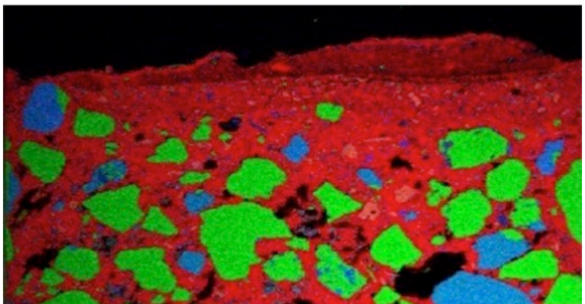


Figure 59 – ST2 (SEM).

Figure 60 represents the analyzed surface of the ST2 sample demonstrating its different chemical compounds. The most relevant compounds are the calcium oxide (CaO) and silicon dioxide (SiO_2), with 53.34 % and 30.04 % respectively. The big squares indicate the clinker was not hydrated. In Figure 59a, the white and lighter parts represent the surfaces rich in aluminium and iron (lighter particles) while the grey and dark areas are rich in silicium (heavier molecules).



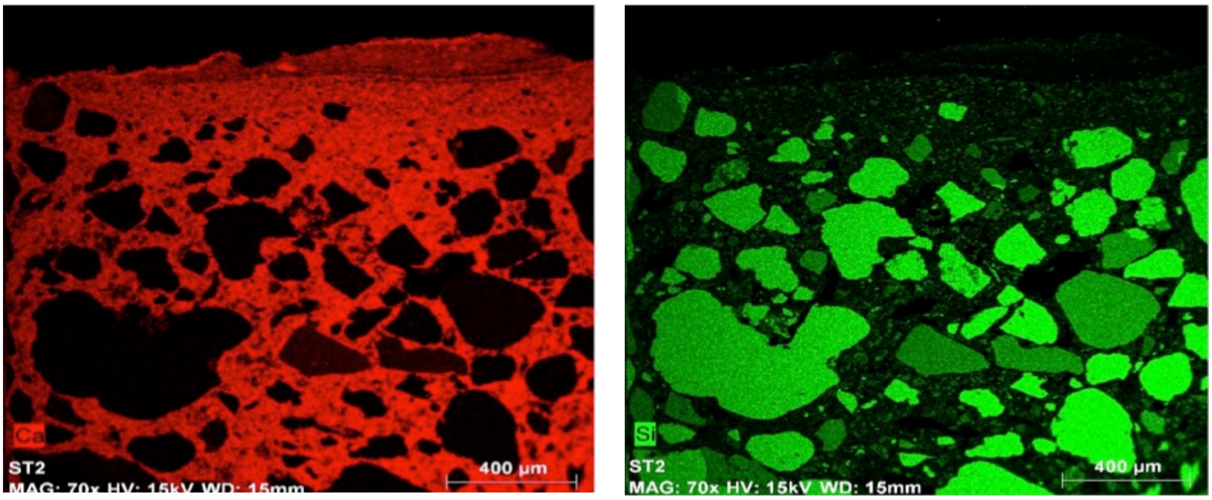
a)



b)

Figure 60 – ST2 chemical composition: a) analyzed surface; b) different compounds.

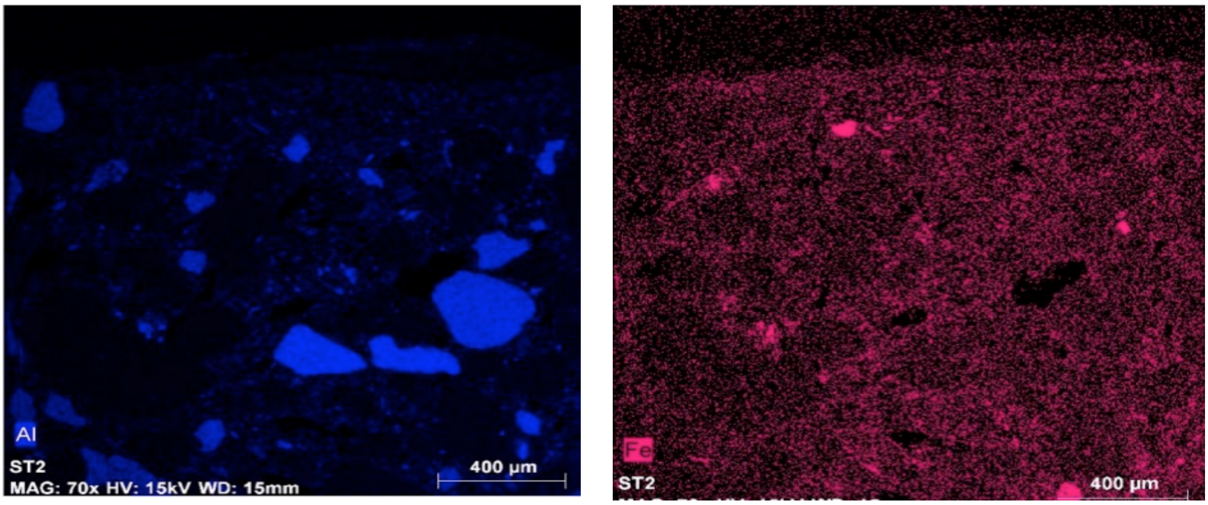
The clinker is mostly divided in 10 % of tricalcium aluminate ($Ca_3Al_2O_6$), 8 % of tetracalcium aluminoferrite ($Ca_4Al_2Fe_2O_{10}$), 20 % of dicalcium silicate (Ca_2SiO_5), 55 % of tricalcium silicate (Ca_3SiO_4), 2 % of sodium/potassium dioxide (Na_2O/K_2O) and 5 % of gypsum ($CaSO_4.H_2O$). The concentrations of calium and silicon in Sample ST2 are shown in Figure 61 (red and green respectively), covering together more than 80 % of the specimen.



a) b)

Figure 61 – ST2: a) calcium concentration; b) silicon concentration.

Also with relevant quantities, aluminium (6.31 %) and iron (4.17) are shown in Figure 62 a and b respectively.



a) b)

Figure 62 – ST2: a) aluminium concentration; b) iron concentration.

Table 2 summarizes the composition of ST2. It reveals a carbonated binder (high content of calcium oxide) and substantial levels of silicon dioxide and aluminium oxide. However, analyzing the whole sample in a single average can interfere the results, since there are different grains with different chemical composition. Therefore, the analysis was performed separately, considering grains with same colour and texture.

Table 2 – ST2 chemical composition.

Element	Percentage (wt. %)
CaO	53.34
SiO_2	30.04
Al_2O_3	6.31
MgO	2.15
Na_2O	0.74
K_2O	2.15
SO_3	0.76
Cl	0.08
TiO_2	0.22
FeO	4.17
MnO	0.03
Total	100.00

For a more accurate analysis, the sample was divided into different regions and different chemical averages were collected. Considering the sections where there is a significant content of calcium oxide (CaO), Table 3 shows the composition of the compounds. They refer to areas that present the same colour and texture, and present homogeneous and lighter surfaces. The numbered sections of the sample can be seen in Figure 63, as well as the division of layers. By analyzing the pictures, it is possible to identify at least two different layers (one a bit darker in the top, probably due to the high content of silicium, and the other lighter in the bottom, may due to the high level of aluminium and iron).

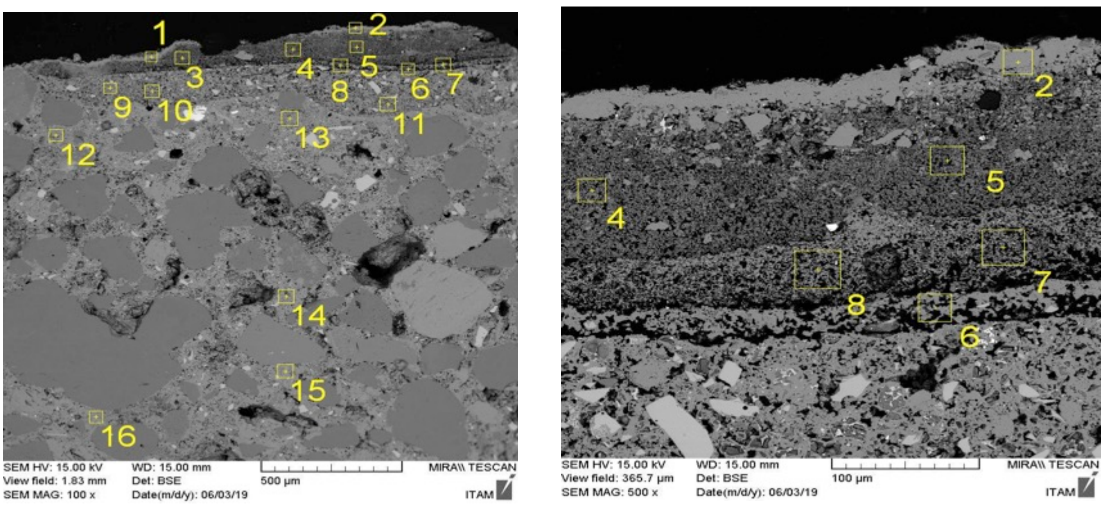


Figure 63 – ST2: a) numbered sections; b) layers division.

Table 3 – ST2 calcium oxide analysis.

Element	Calcium Oxide Analysis (%)							
	1	2	6	9A	10A	12A	14A	15A
CaO	98.01	96.42	95.67	95.71	96.66	90.70	96.1	96.72
SiO_2	0.28	0.97	1.46	1.11	0.61	5.64	1.37	1.33
Al_2O_3	0.12	0.42	0.30	0.13	0.06	1.23	0.21	0.24
MgO	0.22	0.86	1.07	1.06	1.04	0.77	0.99	0.66
Na_2O	0.48	1.07	0.35	0.71	0.41	0.25	0.34	0.06
K_2O	0.05	0.06	0.34	0.64	0.61	0.84	0.22	0.23
SO_3		0.13	0.65	0.28	0.51	0.15	0.56	0.25
Cl			0.05					0.09
TiO_2			0.11	0.13		0.08		0.18
FeO	0.80	0.07		0.23	0.06	0.32	0.19	0.26
MnO								
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Since they present similar chemical compounds, these sections represent grains with similar texture and colour. Figure 64, for example, illustrates sections 9A, 10A and 14A. They all present similar surfaces and are surrounded by bigger and darker aggregates. All other photos regarding the SEM analysis will be presented in Annexes for a better viewing.

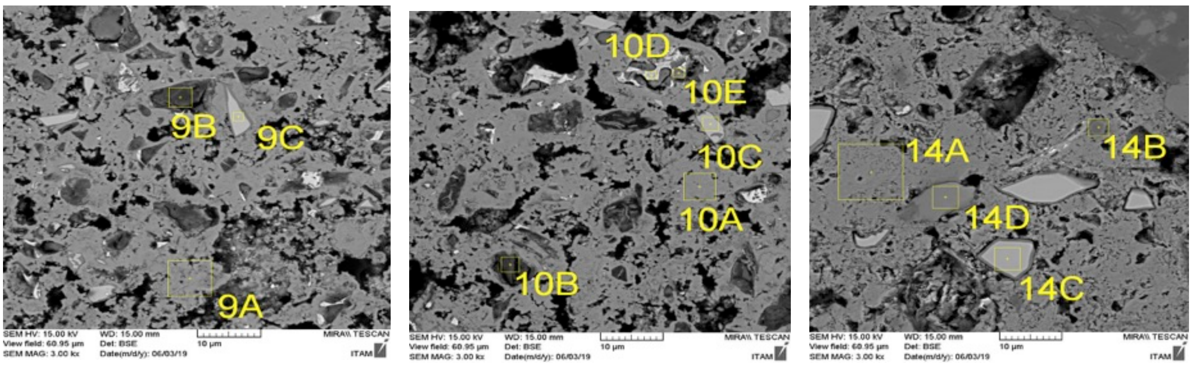


Figure 64 – ST2 sections with calcium oxide relevance.

Table 4 shows the composition of the compounds in sample ST2, and Figure 64 illustrates sections 11B, 12B and 13B. It is possible to observe that these sections belong to homogeneous areas that present a darker colour, maybe due to the high content of silicon (high molecular weight). Also possible to see in Figure 65 the homogeineity of the carbonated binder, with no grains in the surface.

Table 4 – ST2 silicon dioxide analysis.

Element	Silicon Dioxide Analysis (wt. %)							
	9B	10B	11B	12B	13B	13F	14B	14D
CaO	6.95	5.70	1.37		0.21	0.98	0.94	0.87
SiO_2	65.05	67.19	66.50	99.45	99.57	64.03	98.52	60.98
Al_2O_3	8.21	9.35	7.74	0.09		19.64	0.25	18.45
MgO	5.71	2.11	8.66				0.08	
Na_2O	2.16	2.41	2.52			5.95		0.45
K_2O	7.68	9.19	7.60		0.06	8.89	0.06	19.03
SO_3	0.59	0.51	2.00	0.12			0.06	
Cl	0.23	0.18	0.29				0.07	
TiO_2	0.88	0.28	0.85	0.11	0.11	0.16		0.2
FeO	2.53	3.09	2.47	0.23		0.32		
MnO								
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

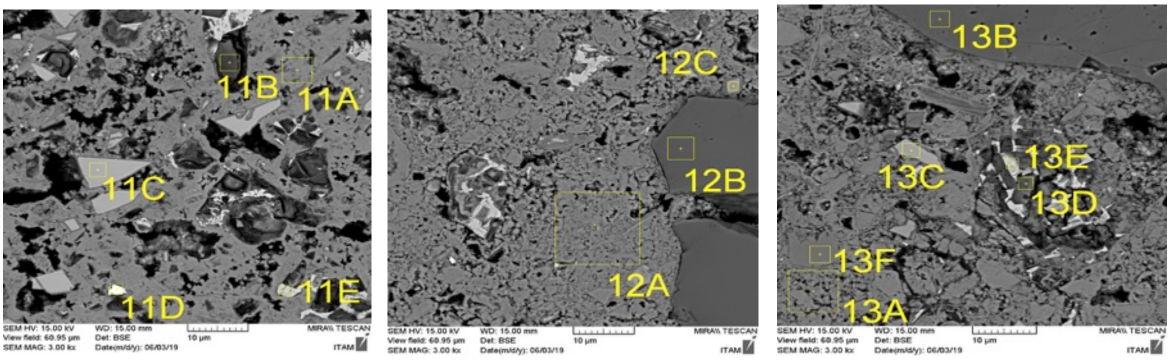
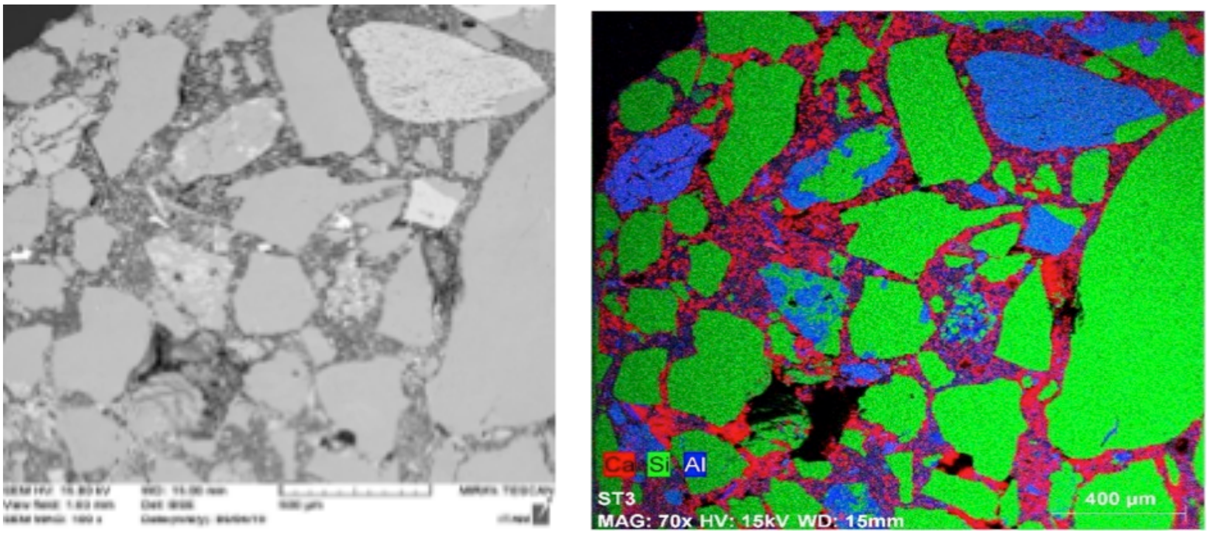


Figure 65 – ST2 sections with silicon dioxide relevance.

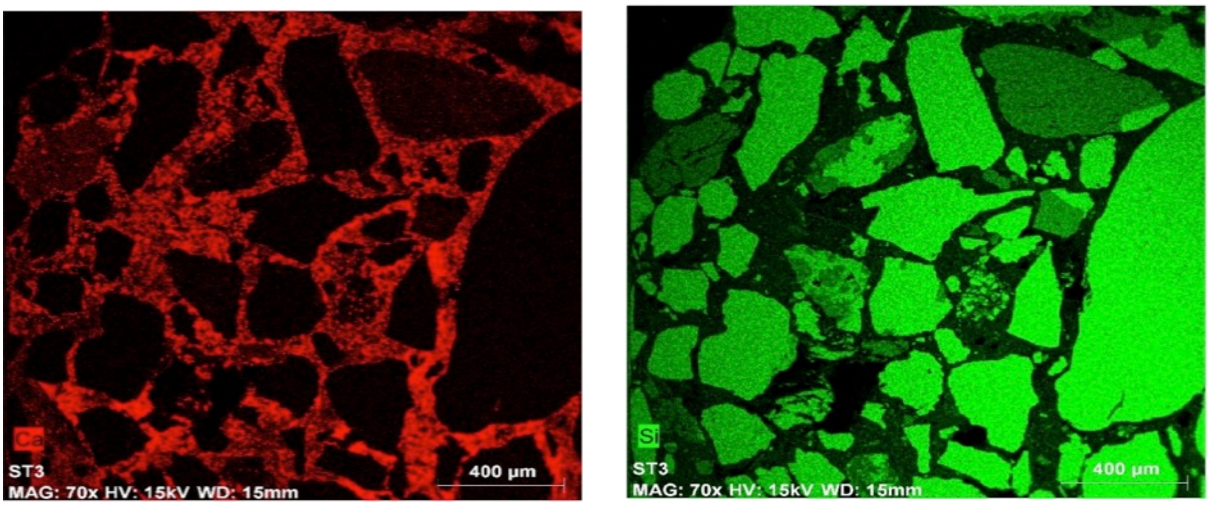
Regarding the ST3 sample, it is possible to see the surface and layers in Figure 66. The most relevant compounds are the calcium oxide (CaO) and silicon dioxide (SiO_2), with 28.51 % and 39.21 % respectively. The concentrations of calium and silicon in Sample ST3 are shown in Figure 67 (red and green respectively), covering together almost 70 % of the specimen.



a) b)

Figure 66 – ST3 chemical composition: a) analyzed surface; b) different compounds.

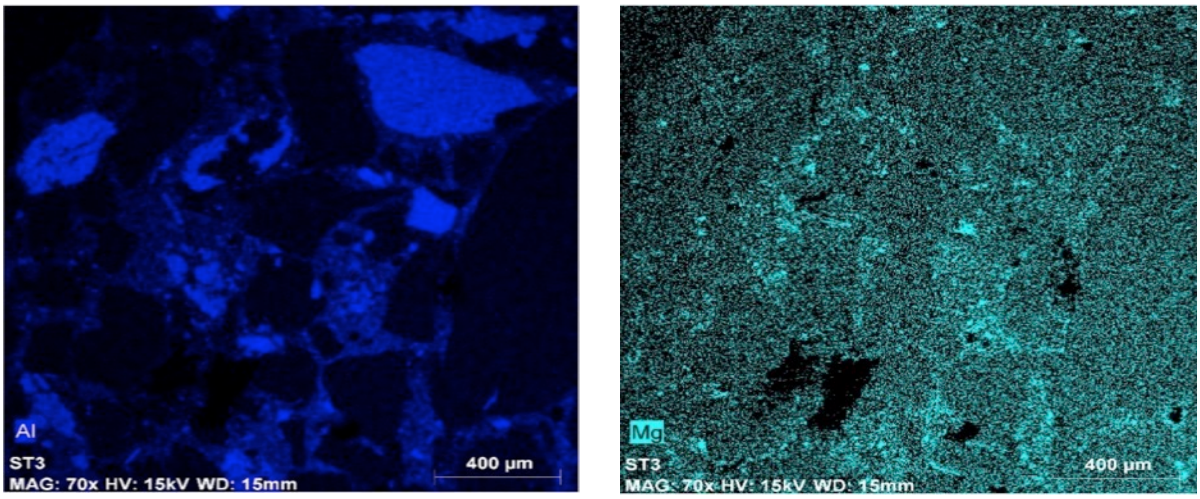
Also with relevant quantities, aluminium (14.00 %) and magnesium (5.131) are shown in Figure 67 a and b respectively. Table 5 summarizes the composition of ST3.



a) b)

Figure 67 – ST3: a) calcium concentration; b) silicon concentration.

Also with relevant quantities, aluminium (14.00 %) and magnesium (5.131) are shown in Figure 68 a and b respectively. Table 5 summarizes the composition of ST3. The numbered sections are seen in Figure 69, for separetly analysis of calcium oxide.



a) b)

Figure 68 – ST3: a) aluminium concentration; b) magnesium concentration.

Table 5 – ST3 chemical composition.

Element	Percentage (wt. %)
CaO	28.51
SiO_2	39.21
Al_2O_3	14.00
MgO	5.31
Na_2O	0.56
K_2O	1.94
SO_3	0.86
Cl	0.43
TiO_2	2.89
FeO	4.50
MnO	1.79
Total	100.00

As Figure 69 is one of the high magnification photos, it is possible to see some degradation mechanisms, such as disruption between porous aggregates leading to a loss of cohesion of the material ow low cement content.

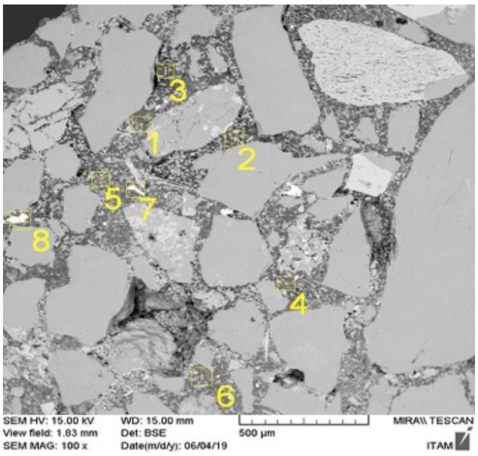


Figure 69 – ST3 numbered sections.

Table 6 – ST2 calcium oxide analysis.

Element	Calcium Oxide Analysis (%)			
	1A	2A	3A	5A
CaO	91.54	96.50	96.68	81.75
SiO_2	5.02	1.46	1.71	3.09
Al_2O_3	1.43	0.33	0.57	5.26
MgO	0.08	0.06		8.14
Na_2O	0.12	0.08		0.18
K_2O	0.17	0.08		0.11
SO_3	1.06	1.25	0.50	0.66
Cl	0.05			
TiO_2	0.21			0.28
FeO	0.30	0.24	0.13	0.52
MnO				
Total	100.00	100.00	100.00	100.00

Among these sections with high level of calcium oxide, the areas 1A, 2A and 3A are presented in Figure 70. They have similar characteristics, being placed in similar grains.

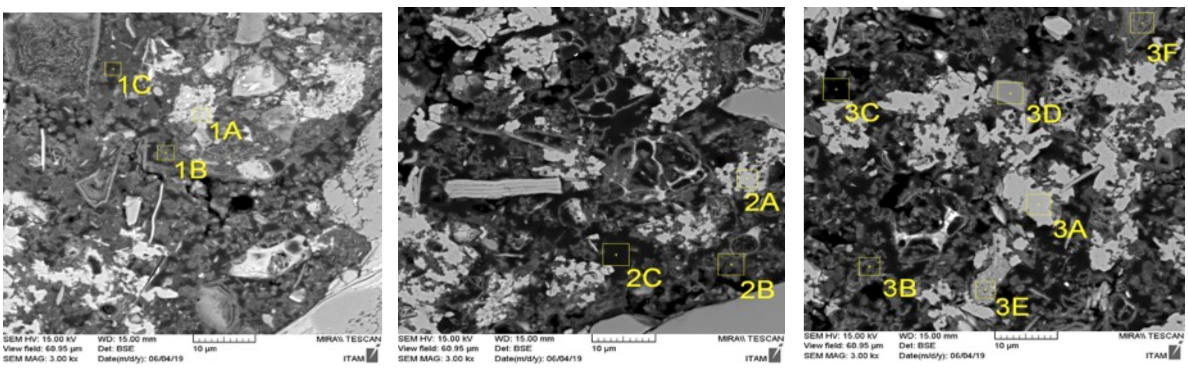
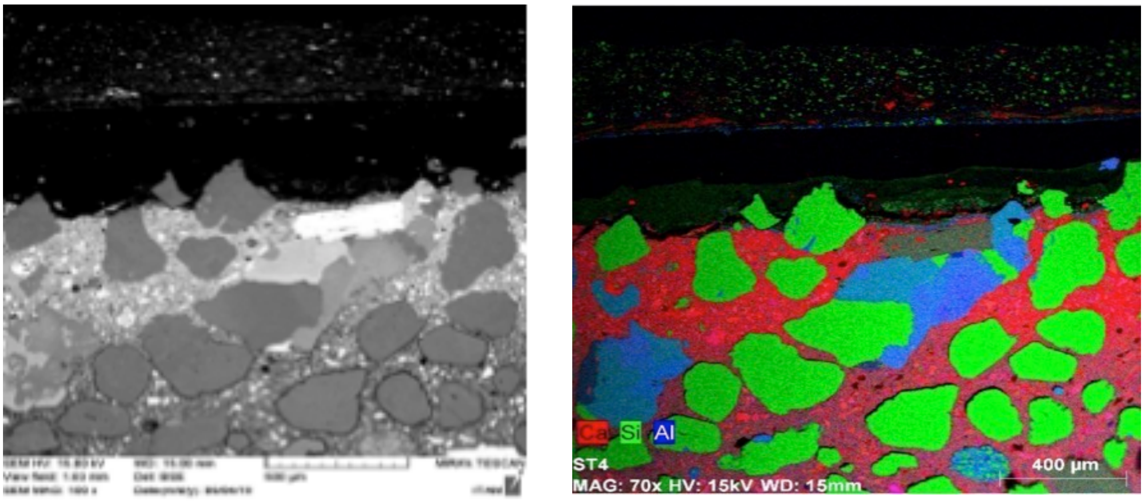


Figure 70 – ST2 sections with calcium oxide relevance.

The same analysis can be done to the other samples. For ST4, the surface and chemical components are seen in Figure 71, with both calcium oxide and silicon dioxide being the most relevant substances, with 41.87 % and 34.37 %. The same approach was performed for ST4 and the others not previously mentioned.



a) b)

Figure 71 – ST4 chemical composition: a) analyzed surface; b) different compounds.

In general, with the results from SEM, it is possible to figure a highl quantity of microporous, which means the relation water-cement is high and, therefore, the concrete is not durable. Also, the big squares indicate that the clinker was not hydrated and the binder is very carbonated. Regarding the shapes of the grains, it is possible to see very angled grains, meaning they are possibly grains of binder.

4.6.2 Thermogravimetry

Thermogravimetry is a technique that measures the change in mass of a material as a function of time at a determined temperature or over a temperature range using a predetermined heating rate. In order to perform thermogravimetric analysis, a microbalance surrounded by a furnace is used. All gains and losses of weight are recorded to plot a graph between weight and temperature over time. For isothermal studies, weight is plotted against a function of time and, for experiments at constant heating rate, weight is plotted as function of temperature (Ramachandran, 2002).

Moreover, degradation mechanisms can be predicted by thermogravimetric analysis. Indeed, it is possible not only to plan replacement before failure and avoid premature replacement but also be used for developing specifications for quality assurance and control tests and formulations (Ramachandran, 2002).

Figure 72 illustrates the thermogravimetric curve for sample ST2. It is possible to see two process that lead to a loss of weight: hydration and carbonation. In the hydrate process, water is expelled dropping the weight at a level of 2.7 %. This happens with a temperature around 400 °C. In the carbonate process, the carbon dioxide (CO_2) is expelled from the calcium carbonate ($CaCO_3$), leaving just the calcium oxide (CaO). This happens between 400 ºC to 800 °C.

The process of carbonation begins when CO_2 dissolves in the pore solution to produce HCO_3^- and CO_3^{-2} ions. These ions react with Ca^{+2} from calcium hydroxide (CH), calcium silicate hydrate (C-S-H), hydrated calcium aluminates and ferro-aluminates and precipitate as various forms of calcium carbonate ($CaCO_3$), silica gel, hydrated aluminium and iron oxides (Borges, 2009).

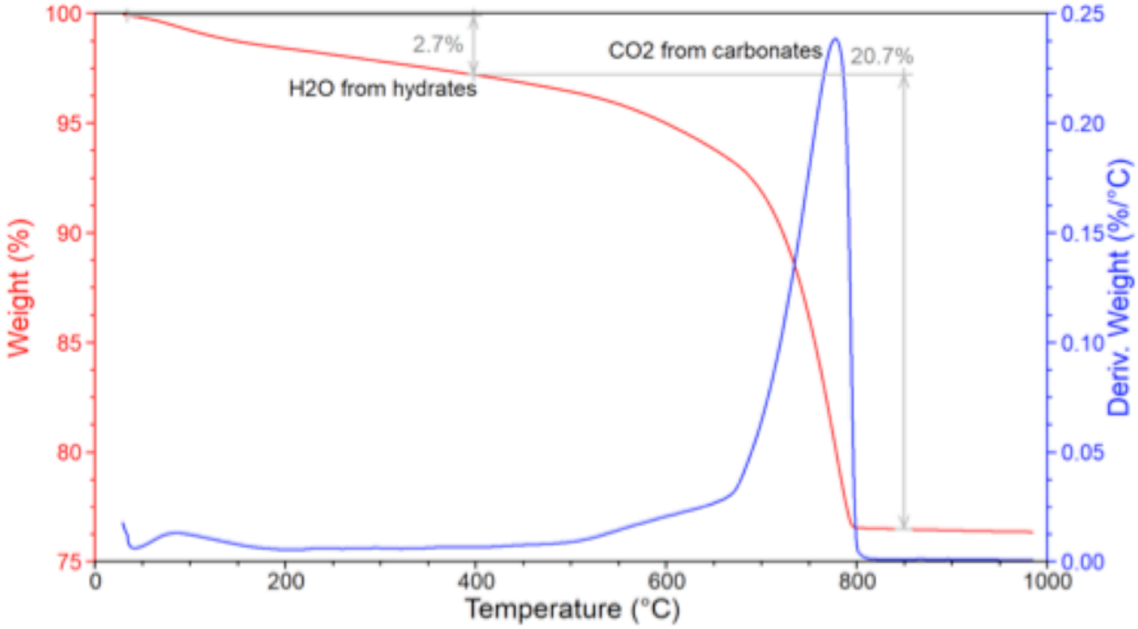


Figure 72 – ST2 thermogravimetric analysis.

Same analysis can be done for the other samples. Figure 73 shows the variation of the weight of the sample ST3 over temperature range. The hydrate process has a higher intensity than the ST2 sample (6.2 %) while the carbonate has a bit lower intensity (19.7 %). Carbonate decreases drastically the weight at a temperature of around 760 ºC, same for the previous analysis.

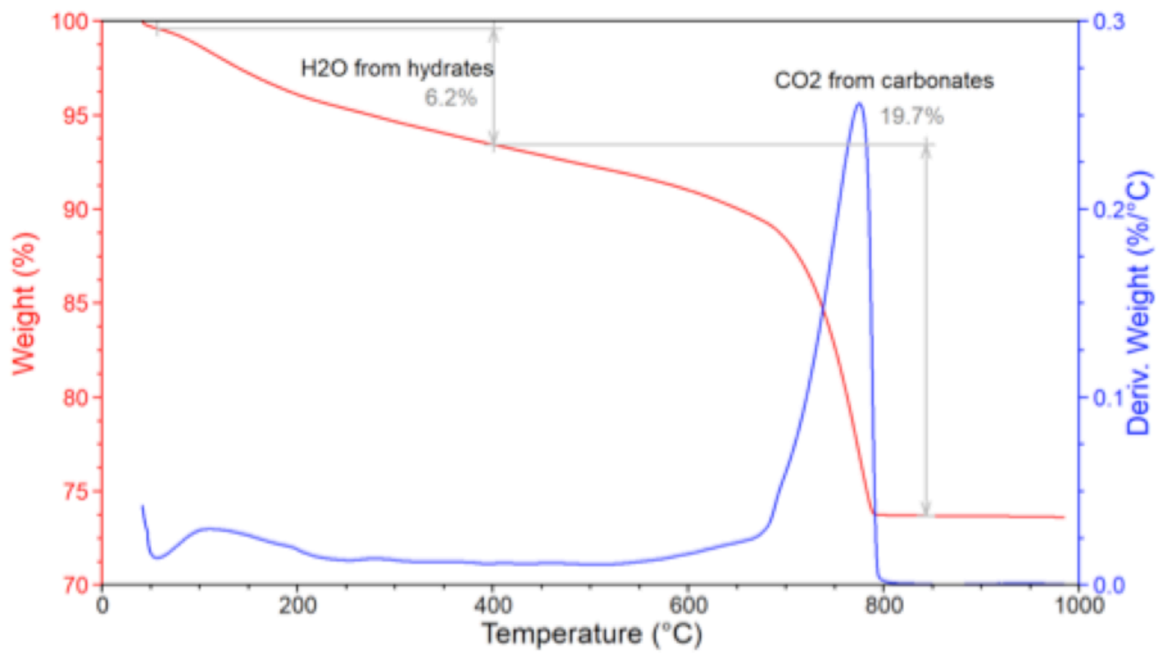


Figure 73 – ST3 thermogravimetric analysis.

For sample ST4 (Figure 74), there is a little difference: there is one more reduction process, the portlandite reaction. First, the hydrate process (with the highest level of 10.3 %) occurs till 400 ºC, then another quantity of water expelled from portlandite (1.2 % till around 520 ºC) and then carbonate loss (the lowest level with 3.3 % of loss).

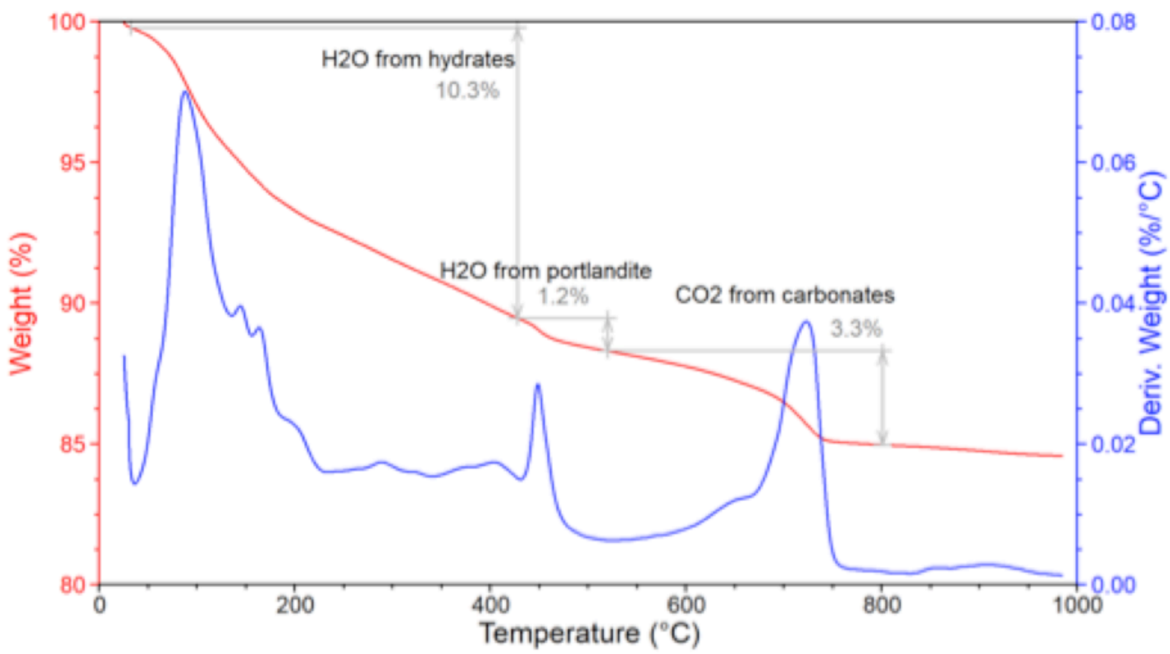


Figure 74 – ST4 thermogravimetric analysis.

4.6.3 Salt Content

Overall, the values of sulfate (SO_4^{-2}) are less than 200 mg/L or more than 400 mg/L; and the values of nitrate (NO^{-3}), nitrite (NO^{-2}) and chlorine (Cl^{-}) are equal to zero. Since the merck stripes are of low precision, more precise chemical analysis should be performed to ascertain the salt content. Below, Table 7 summarizes the results.

Table 7 – Salt content results.

Salt Content					
Ion	**Ion content range measured with analytical strips**				
	ST1 total (mg/L)	ST1 binder (mg/L)	ST2 binder (mg/L)	ST3 binder (mg/L)	ST4 binder (mg/L)
Sulfate	<200	>400	<200	<200	<200
Nitrate	0	0	0	0	0
Nitrogen Dioxide	0	0	0	0	0
Chlorine	0	0	0	0	0
pH	8.0	8.0	8.5	7.5	7.5
Total weight (g)	11.970	11.970	16.000	3.900	30.870
Aggregate weight (g)	8.155	8.155	14.500	2.350	26.030
Binder weight (g)	3.815	3.815	1.500	1.550	4.840

The stripes for the analysis of chloride anions allow the detection of solution concentration with chloride content approximately equal to 500, 1000, 15000, 2000 and 3000 mg/L. The stripes for the analysis of sulfate anions allow the detection of solution concentration with more than 200 mg/L of sulfate ions. The detection scale comprises the following concentration intervals: <200, >400, >800, >1200 and >1600. And the stripes for the analysis of nitrate and nitrite allow the detection of nitrate in solutions with concentration of this anion approximately equal to 10, 25, 50, 100, 250 and 500 mg/L and the detection of nitrite in solutions with concentration of this anion approximately equal to 1, 5, 10, 20 and 80 mg/L. The tests results are represented in Figure 75.

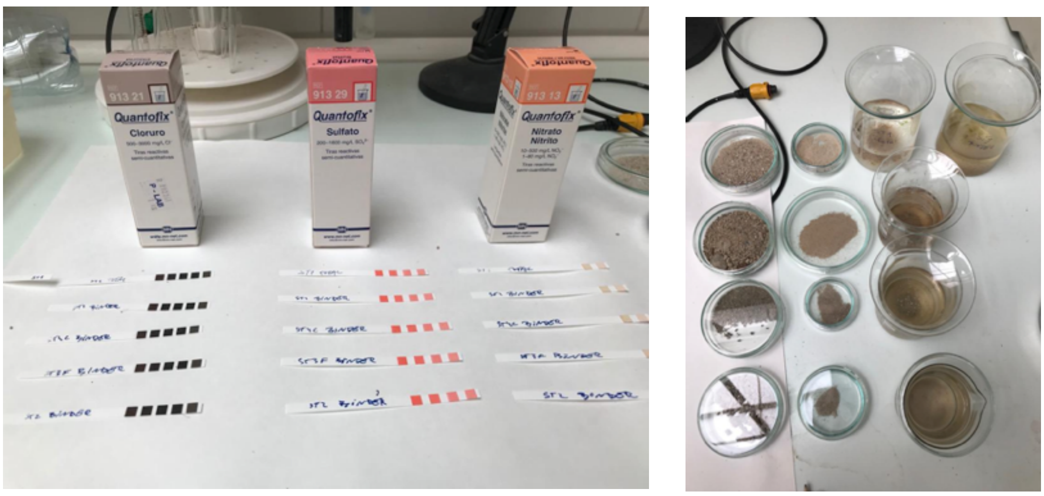


Figure 75 – Salt content analysis.

Analyzing the degradation mechanisms observed with SEM, it is possible to correlate them with the values of pH found in the salt content tests. The lowest pH values refer to samples ST3 and ST4 (7.5 each), while the highest alkalinity was found in sample ST2 (8.5). Therefore, ST2 may have suffered less acidic attack since the alkalinity was not dropped as the other samples.

4.7 Current State of Conservation

In this section, the deterioration mechanisms of the stadium are presented, with their respective causes of damage. The Strahov Stadium is like an Atlas of concrete damage types. Everywhere there are different types of damages, and the most relevant ones are, according to the Monument Diagnosis and Conservation System (MDCS), disintegration, cracks, surface changes, biological growth, deformation and reinforcement corrosion.

4.7.1 Disintegration

Disintegration is a deterioration mechanism that can occur both in the interior and exterior of the concrete material. When it occurs in the interior, there is a loss of cohesion, leading to pop-outs, erosion, dusting or crumbling. When it happens between two layers, it can be related to scaling, spalling and exfoliation. All of these mechanisms were found in Strahov stadium and need maintenance.

Pop-outs represent cavities in the concrete surface that result from the loss of aggregate. It can be due to a disruption between a porous aggregate, saturated with water, and the surrounding cement matrix during freezing periods. (MDCS). Figure 76 shows the presence of pop-outs in the stadium. They were found in the ceiling of a corridor in North tribune, on the third access (from left to right) to the grandstand, showing a cavity due to the aggregate loss.

Figure 76 – Pop-outs in North tribune.

Also presented in high scale, there is the mechanism of erosion and disintegration of cement matrix. In this case, the cement disappears gradually, locally exposing the aggregates. Erosions are maybe due to external impacts or acid rain. Acids dissolve the cement and expose the aggregates since concrete has low resistance against acids, propitiating a good scenario for corrosion by water and wind. Moreover, too strong cleaning procedures can also lead to erosion of concrete (MDCS). Therefore, the exposure to wind and weather contributes to erosion, as exemplified in Figure 77, which shows erosion in the columns of the left section in North tribune.

Figure 77 – Concrete erosion in North tribune.

Moreover, the presence of dusting is clearly seen. It refers to a fine powdery material that can be expelled from the concrete surface. It probably happens in the construction phase of the structure during the transport of fine particles to the concrete surface due to bleeding. In cases of excessive bleeding, the surface becomes weak. Also, a too quickly drying surface can lead to a weakening structure since part of the surface will be unhydrated (MDCS). Figure 78 illustrates presence of dusting in the wall and ceiling of the second entrance to the grandstands in North tribune.

Figure 78 – Dusting mechanism in North tribune.

Also related to disintegration, there is the crumbling mechanism, that occurs when concrete crumbles into pieces, probably due to low cement content or exposure to freeze-thaw cycles (MDCS). Figure 79 highlights crumbling presence in the top of a concrete wall and in the bottom of a beam in North tribune, close to the second grandstand access.

Figure 79 – Crumbling in North tribune.

Regarding disintegration between layers, there are the mechanisms of scaling, spalling and exfoliation. Scaling is observed when the concrete surface shows loss of particles, mainly mortar with superficial damage. This happens maybe due to freeze-thaw cycles, combining sometimes with deicing salt (MDCS). Scaling can be seen in Figure 80, which represents the stair of one of the access to the grandstands and the top of a corridor wall in North tribune.

Figure 80 – Scaling in North tribune.

Also regarding layering, there is the spalling mechanism, which is detachment of a relatively thick layer of the concrete, probably caused by the large volume of rusting iron/steel caused by reinforcement corrosion. It is mainly preceded by cracks along the reinforcement (MDCS). It is possible to see spalling in Figure 81, that represents the bottom of a beam and the top of a column in a North tribune corridor.

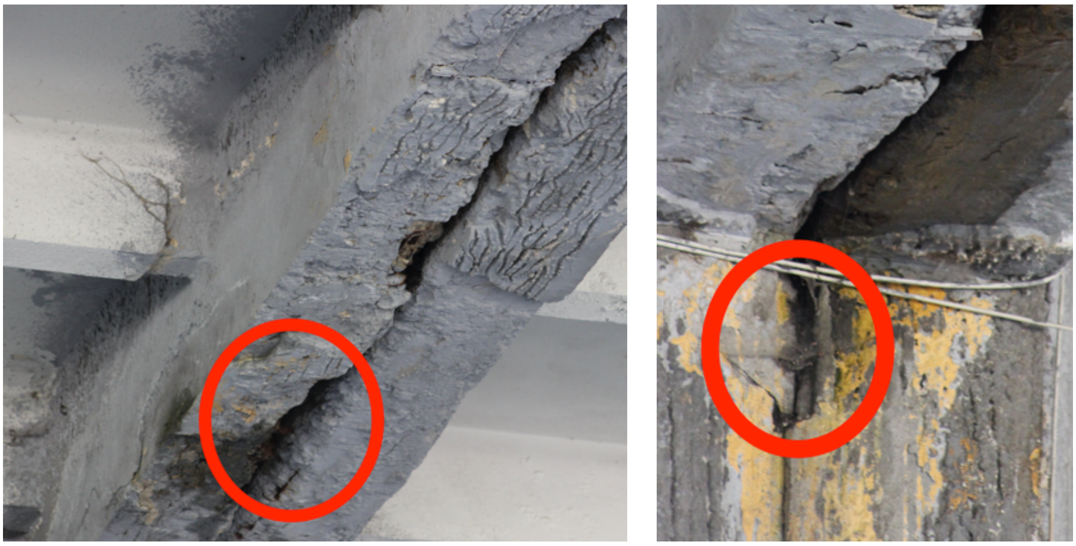


Figure 81 – Spalling occurrence in North tribune.

And the exfoliation referes to the detachment of thin layers of concrete surface. It is possible to detect exfoliation just by tapping on the surface and this mechanism may happen due to the fact that ai rand bleeding water get stuck in a dense concrete surface during hardening (MDCS). Figure 82 reveals exfoliation in the stadium, found in almost all columns of North tribune.

Figure 82 – Exfoliation in the column in North tribune.

4.7.2 Cracks

Another common deterioration mechanism found in both South and North tribunes are the cracks. They occur whenever the tensile stress overcomes the tensile strength, and can be classified by their geometry (orientation, width, depth, interconnection), quantity (singular or multiple), and relation to reinforcement. Overall, they negatively influence the concrete durability and have maximum allowable widths (e.g. 0.4 mm for reinforced concrete and 0.3 for prestressed concrete) (MDCS).

Regarding the non-connected cracks, they can be parallel or individual. Parallel cracks usually have regular distances from each other (Figure 83a) and may occur due to reinforcement corrosion, showing rust stains along the length. In cases with higher distances between the cracks (Figure 83b), the possible cause is maybe restrained thermal deformation. Cracks in Figure 82 are from the top of the grandstand access corridor.

a)

b)

Figure 83 – Non-connected cracks: a) regular distance; b) irregular distance.

Also related to the non-connected cracks, there are the individual cracks (Figure 84), that neither are interconnected nor form a pattern with other cracks. A correlation between load bearing system, reinforcement layout, orientation and construction phase in which crack occurred is necessary to understand the main causes of the formation of cracks. Overall, they are mainly due to thermal stresses, settlement, shrinkage, corrosion, mechanical impact or overloading (MDCS).

Figure 84 – Individual cracks in North tribune corridor.

Regarding the interconnected cracks, they can be either map-cracking, crazing or geometric pattern forming. Both map-cracking and crazing refer to interconnect cracks forming random patterns. The possible causes can be discovered by the age of concrete when the crack appeared. If cracks appeared in hardened concrete, a chemical or physical reaction can be the cause; if they appeared when the concrete was still fresh, they may have been caused by plastic shrinkage. Overall, they are visible at surface and can be caused by expansive, internal reactions or ettringite formation (MDCS). Figure 85 illustrates map-cracking in the Strahov stadium,

Figure 85 – Map-cracking in North tribune.

4.7.3 Surface Changes

When the concrete surface has change its original colour or texture, the present of deposits may be the cause. The deposits can be endogenous (inside the material, e.g. calcitic material, salt efflorescence and crypto-florescence) or exogenous (outside the material, e.g. soiling and graffiti). Surface changes can be related to chromatic alteration, superficial irregularities and deposit (MDCS).

Chromatic alteration happens due to damaging processes that directly affect the surface (e.g. water penetration, chemical reactions or sun radiation). They can refer to discolouration, fading, moist spots and linear colour change. Regarding discolouration, one of the causes can be high temperatures, turning the colour into pink and yellowish (Figure 86), or the use of ground granulated cement as a binder, turning the colour into blueish (MDCS). Figure 86 exemplifies chromatic alteration in the stadium, found in a concrete wall of the North tribune.

Figure 86 – Chromatic alteration in concrete wall.

Regarding the fading processes, they can occur by carbonation, oxidation, leaching of pigments and use of less durable pigments (MDCS). Moist spots occur due to high moisture content, making the surface locally darker, as seen in Figure 87, taken from both concrete beams and floors of a corridor to the grandstands of North tribune.

Figure 87 – Moist spots in a concrete wall.

Regarding superficial irregularities, they can be classified as voids and segregation. They are both usually caused during construction phase (e.g. poor workmanship or inadequate mix design). The voids can be related to bug holes (caused by air when concrete is not adequately compacted) or rock pockets (due to leakage of cement paste near formwork joint or incorrect placing and compaction of the concrete) (MDCS). Figure 88 illustrates rock pockets in a concrete column and in the corridor ceiling in North tribune.

Figure 88 – Rock pockets in a concrete column.

Regarding the deposits, there are five subcategories: soiling (due to the deposition of dirt, e.g. dust, particles, soot or due to calamities), staining (due to reinforcement corrosion, pyrite presence in iron or presence of tying wires pieces), graffiti (paint due to act of vandalism), encrustation (deposit of leached constituents, due to seepage or leakages) and efflorescence (due to high presence of salt and moisture, as a result of capillary transport) (MDCS). It is possible to see graffiti all over the stadium; Figure 89 illustrates the presence of grafiti on the concrete walls of the North tribune.

Figure 89 – Graffiti on the walls of North tribune.

4.7.4 Biological Growth

Biological growth is also a common deterioration mechanism found in the stadium. Totally, there are seven subdivisions: higher plants, mosses, biofilm, algae, lichens, liverworts and moulds. The higher plants form a category of plants in regions where there is moisture and nutrients. Their roots can increase cracks over time and are mainly present in exterior walls and flat roofs exposed to rain or leakages. Materials with disintegration and cracks are more prone to develop higher plants (MDCS). FIgure 90 illustrates the presence of higher plants on the grandstands of the North tribune, more specifically in the bottom rows of bleachers, close to the field, where there is a higher exposure to sunlight.

Figure 90 – Higher plants on the grandstands of North tribune.

The mosses are small plants and grow on damp and shady locations. They can appear in green and brown forms and do not have roots. They are mainly due to freeze-thaw cycles and material deterioration under low levels of pH. Biofilm is a layer that can be brown, black or green and appear on the surface. It consists of algae, fungi and bacteria. They occur due to environmental conditions such as moisture and temperature (MDCS). Figure 91 represents biofilm on the surface of concrete walls on North tribune.

Figure 91 – Biofilm presence in North tribune.

Algae can grow in both internal and external environments. It appears usually green on alkaline surfaces. In order to grow, they require light, nutrients and carbon dioxide, specially in bad drying conditions (MDCS). Figure 92 shows algae in the corner of concrete walls under the stairs of one of the accesses to the grandstands of North tribune.

Figure 92 – Algae presence on concrete walls of North tribune.

4.7.5 Deformation

Deformation is a deterioration mechanism that can be divided into displacement and bending. It is visually seen when the original form or location of the structural element has changed. Under deformation, the element has a change of volume or a deviation from its original form. The displacement can be horizontal or vertical and often appear with cracks. They occur mainly due to foundation problems and external impacts. The bending is usually perpendicular to the axis of the element, without modifying its cross-section. It happens mainly due to a combination of dead load, own weight and creep. Always when there is an excessive bending, there is also cracking. It can also occur due to low structural capacity and long-term exposure to a certain load (MDCS). Figure 93 illustrates bending in junction of beams and slabs, in the corridor to the grandstands in North tribune.

Figure 93 – Bending in the junction of beams and slabs.

4.7.6 Reinforcement Corrosion

Reinforcement corrosion can reveal deteriorations such as corrosion, deformation and mechanical damage. They can corrode under certain circumstances and show different symptoms. Overall, they can be related to rust layers, pitting and loss of rebar diameter. The rust layers diameter, in addition to the rebar, exceeds the original diameter of the bars. In this scenario, the concrete is always cracked or has spalled in the affected area. They occur mainly because of corrosion due to carbonation, chloride attack or stray currents. Corrosion can be enhanced with cracks and voids since carbon dioxide and moisture can easily penetrate the concrete (MDCS).

The pitting mechanism occur due to chloride attack. The chloride sources can be either internal (e.g. calcium chloride) or external (e.g. seawater or deicing salts). Since pitting can be deep, it can severely affect the strength of the reinforcement and possibly the global stability of the structure (MDCS). Figure 94 shows pitting on the bottom of a beam in the corridor of the stairs and on the bottom of column in the access corridor to the grandstands in North tribune.

Figure 94 – Pitting reinforcement corrosion in North tribune.

There is also the loss of rebar diameter, when there is a local or even complete lost of the bar diameters. This happens mainly because the steel bars dissolve when corrosion occurs over its cross-section. When this happens, it is possible to see different concrete types (e.g. brownish layers and coarse aggregates) (MDCS). Figure 95 illustrates a loss of rebar diameters in a interior column close to the stairs in North tribune. In the second photo, it is possible to see that the diameter of the bar changes along its axis; it is not homogeneous.

Figure 95 – Loss of rebar diameter in column of North tribune.

4.8 Recommendations

After analyzing the conditions of the stadium structure, and also evaluating interventions made on similar structures, such as the Brazilian stadiums Maracanã, Morumbi and Serra Dourada, it was possible to propose conservations and repair maintenances. Before the proposals, below are some summaries about these stadiums interventions:

Maracanã Stadium (Rio de Janeiro, Brazil), shown in Figure 96, was built in 1950 and suffered interventions between 1999 and 2001 and then in 2005 and 2006. The stadium has a capacity of 80,000 people and hosted many special concerts and the most important sports competitions (e.g. FIFA World Cup in 1950 and 2014, America Cup in 1989 and 2019, FIFA Confederations Cup in 2013 and Summer Olympics in 2016).

- Most relevant deterioration mechansisms: water infiltrations, concrete disintegration by leaching or by displacement, reinforcement corrosion, cracks, carbonation, efflorescence and mold discolouration (Jordy, 2006).
- Possible causes for these mechanisms: design flaws, atmospheric aggressive agents, percolation water, execution flaws, vandalism, waterproofing deficiencies, lack of maintenance, contributing to the loss of capacity strength, possible risks of ruin and discomfort to the users, besides social losses due to the numerous cyclical works carried out for recovery since the inauguration (Jordy, 2006).
- Interventions: structural recovery and reinforcement of the support frame of slabs, construction of new upper slabs, recovery of pillars and protection system for cover structures (Jordy, 2006).

Figure 96 – Maracanã Stadium (Jordy, 2006).

Mineirão Stadium (Belo Horizonte, Brazil), shown in Figure 97, was built in 1965 and suffered interventions in 2010. The stadium has a capacity of 65,000 people and also hosted several concerts and international tournments, such as FIFA Confederations Cup in 2013, FIFA World Cup in 2014, Summer Olympics in 2016 and America Cup in 2019.

- Most relevant deterioration mechanisms: reinforcement corrosion, water infiltration, cracks and surface changes (Jordy, 2006).
- Possible causes for these mechanisms: execution and fabrication flaws, exposure to pollutant agents, lack of maintenance and waterproofing deficiencies (Jordy, 2006).
- Interventions: demolition of part of the lower bleachers, structural repairs, withdrawal of seats, structural recovery, demolition of the field by 3.4 m to improve visibility, construction of a new coverage, new seats and other internal adjustments (Jordy, 2006).

Figure 97 – Mineirão Stadium (Jordy, 2006).

Serra Dourada Stadium (Goiânia, Brazil), shown in Figure 98, was built in 1975 and suffered interventions in 2011. The stadium has a capacity of 55,000 people and also hosted many concerts and special sports competitions (e.g. America Cup in 1989 and Libertadores Cup in 1981).

- Most relevant deterioration mechanisms: cracks, biological growth, vandalism, reinforcement corrosion, surface changes, water infiltration and concrete disintegration.
- Possible causes for these mechanisms: lack of maintenance, execution flaws, water proofing deficiencies and exposure to pollutant agents (Jordy, 2006).
- Interventions: reinforcement of the support frame of the slabs, demolition and reconstruction of the external concrete walls and reconstruction of the access roads.

Figure 98 – Serra Dourada Stadium (Jordy, 2006).

These Brazilian stadiums had similar deteriorations with the Strahov stadium. Analyzing their successful interventions can help defining good proposals for conservation in Strahov. Some of these interventions in Brazil are still ongoing (e.g. reconstruction of the external concrete walls in Serra Dourada stadium), but it is already possible to see great results in terms of conservation techniques.

4.8.1 Proposal for Conservation

By analyzing these interventions and the deterioration mechanisms observed in Strahov, it is recommended to consider the following conservation techniques: concrete removal and replacement technique for displacements that occur in the interior of the concrete (e.g. loss of cohesion, pop-outs, erosion, dusting and crumbling); grouting and injection technique for cracks and superficial irregularities; surface treatment technique for surface changes (e.g. calcitic material, salt efflorescence, crypto-florescence, soiling and graffiti) and for displacements that occur in the concrete surface (e.g. scaling, spalling and exfoliation); electrochemical technique for cracks, reinforcement corrosion and superficial changes; and strengthening technique for reinforcement corrosion and deformation. These key interventions can prevent the observed damage mechanisms to continue scaling up.

Moreover, further analysis studies should be done in order to efficiently repair the damages in all tribunes of the stadium (especially East and West tribunes, which were not studied for this work). It is recommended to implement a management system in building maintenance for a technical and multidisciplinary approach. Regular maintenance should be performed in order to avoid further deterioration mechanisms.

4.8.2 Architectural Plans

Sometimes, repairing the deterioration mechanisms individually may cost a lot of money and time consuming. In some cases, when the building is too deteriorated, demolishing and reconstruction can be worth it. As Strahov stadium is facing a serious scenario of deterioration, some proposals were suggested to transform the complex venue in a more attractive and useful structure, and some of them are totally different from the original plan.

One of the proposals was the implementation of a hotel complex in part of the stadium area, so that the number of tourists could increase, consequently leading to the growth of the economy. This idea came in 2018 from PhD Veronika Indrová, who was trying to find a general solution for the stadium. However, she would implement the flats under the grandstands, which would still keep the original format. This may not be the best solution since there is no reason to keep the bleachers after demolishing part of the grass field.

Another proposal was turning the stadium into residential apartments. All the structure would be demolished and, instead of rebuilding a new stadium, implementing a new complex of apartments with a leisure area. This would definetly kill the history behind the Strahov stadium, which would be very disappointing.

The proposal I would come up with is turning Strahov stadium into a great training center and sports venue. As it is already used as training center for Sparta Prague, it would be more than important to create a five-star sports complex, which would make Sparta Prague one of the most prepared soccer teams in Europe.

Indeed, Sparta Prague is the most relevant soccer team in Czech Republic, winning 21 Czechoslovak First League and 12 Czech First League, totalizing 33 national league, almost the double than their main rival (Slavia Prague). Therefore, a team with such a great history and competitiveness deserves a great training center.

In order to efficiently perform the construction of this new idealized training center, the original design project of another training center would be used as architectonic structure: Serrinha complex, located in Goiânia/Brazil, same city of Serra Dourada Stadium, previously described. Among the advantages of this new complex, the venue would contain:

- An official stadium with capacity for 10,000 people;
- A covered gym with capacity for 3,000 people;
- A complete concentration structure for athletes;
- Two training camps for the School of Sports Initiation;
- A 25 m semi-Olympic, covered and heated swimming pool for Sports Initiation;
- A parking lot for 300 vehicles;
- Two sand courts for lighted volleyball and football;
- A track for cooper with 1 km;
- An area available for partying.

The new sportive complex would fit in the Strahov area and would definetly be beneficial not only to the AC Sparta Prague, but also to the community and the city in general. Figure 99 illustrates the complex of Serrinha, Goiânia, and shows how the new architecture of Strahov complex would look like.

Figure 99 – Serrinha Complex (Goiás, 2019).

5. CONCLUSIONS & FUTURE PERSPECTIVES

After the damage survey and the monitoring analysis, it was evident that a estructural assessment of the Strahov Stadium is required. The high level of deformation and decay is a concern for both the safety of the people and for the conservation of the historical monument, which is a symbol of the town of Prague.

This thesis project is focused on two fundamental aspects: the conservation of a 20th cent. concrete building (the Great Strahov Stadium), and possible contribution to the improvement of the recent glossary available for the description of concrete anomalies Monument Diagnosis Conservation System (MDCS).

The analysis of this thesis was performed considering only North and South tribunes and was used to propose conservation techniques for the stadium. Overall, the main deterioration mechanisms found onsite were concrete disintegration, cracks, surface changes, biological growth, deformation and reinforcement corrosion. In order to solve these damages, or at least mitigate future problems, the main conservation techniques proposed were the removal of damaged concrete and respective replacement, grouting and injections technique, surface treatments technique, electrochemical technique, and strengthening technique.

Moreover, the Monument Diagnosis and Conservation System (MDCS), which was used to support the knowledge of the damages related to this reinforced concrete structure, was validated but still needs some improvement for better searching and understanding. Indeed, the most relevant deterioration mechanisms are found in the System but they can be better addressed, with better photos and better descriptions. Some of the mechanisms do not even have photos.

Regarding the stadium, it is unquestionable the importance that Strahov had in the last century. It is one of the biggest stadiums in Europe and hosted lots of important events over the last decades. The complex of the stadium had a great impact on society during 20th century but it is now quite abandoned, with lots of deterioration mechanisms that need repair. Great part of the tribunes are not even open for people anymore due to the poor condition of the structure.

It is scary to see the negative impacts a maladministration can cause in a structure. Clearly, there is no maintenance procedures, nor conservation approaches, nor respect to such important construction. The stadium is slowly sinking into its own history, under the responsibilities of people unconcerned with its future. If it continues this way, the damages will be even more intense and the only solution will definetly be the demolishion and reconstruction.

In order to revert this scenario, it is urgent that the administration and managers review their management politics. The willingness to solve the current structural problems must be stronger than ever was. From the moment that this mentality of really taking care of the stadium is put into practice, then the following actions must be taken: 1) regular maintenance strategies, with efficient inspection, cleaning and anomaly repair, so that the observed deterioration mechanisms can be repaired or mitigated; 2) a plan for futher analysis must be taken into account in order to better evaluate the current state of all tribunes; 3) the proposals recommended in this thesis are relevant and must be considered to be applied in situ.

To conclude, it has been demonstrated that it is necessary to keep monitoring last century buildings in order to prevent structural damages and possible collapses. The more a structure is abandoned, the more it is prone to suffer deterioration. Buildings with such importance for the society, such as the Strahov Stadium, deserve to be well conserved so that they can continue with their legacy for future generations. Further analysis in view of its conservation and maintenance strategies are necessary to ensure the safety of the stadium.

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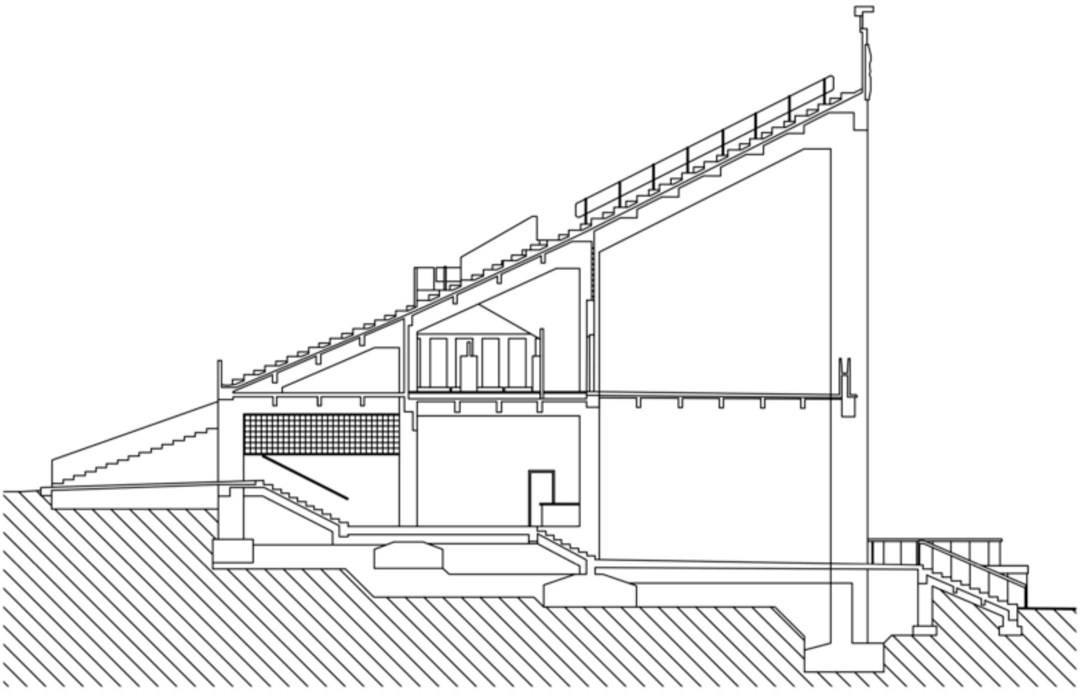
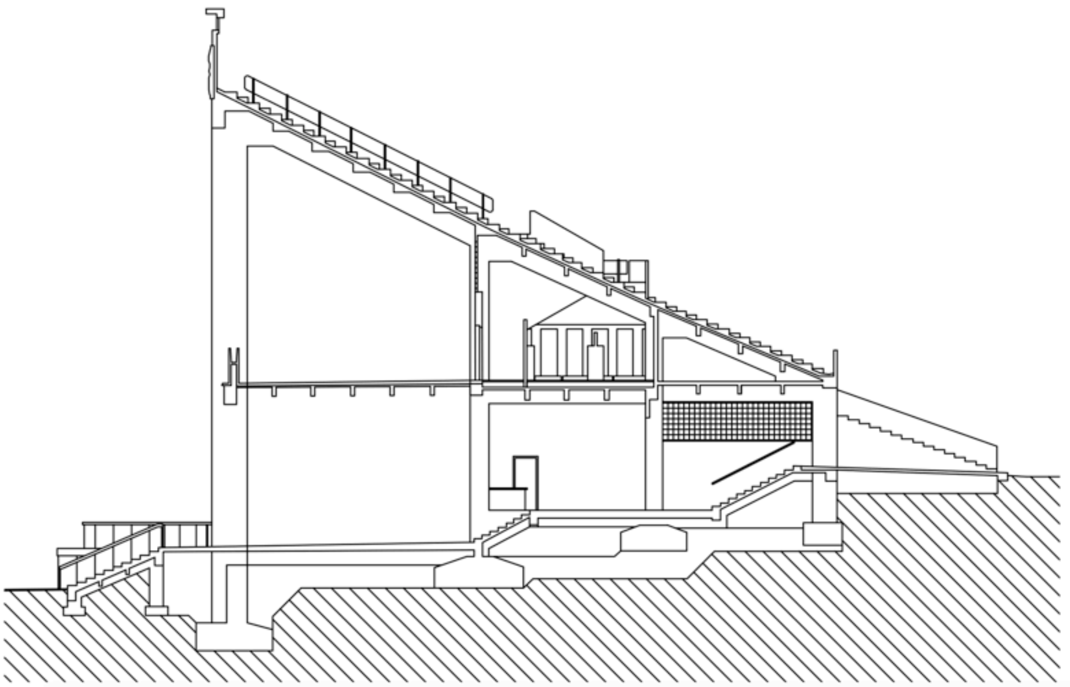
C 496/C 496M – 04 Standard TestMethod for Splitting Tensile Strength of Cylindrical Concrete Specimens and the European standard *BS EN 12390-6:2009 Testing hardened concrete Part 6: Tensile splitting strength of test specimens.*

7. ANNEXES

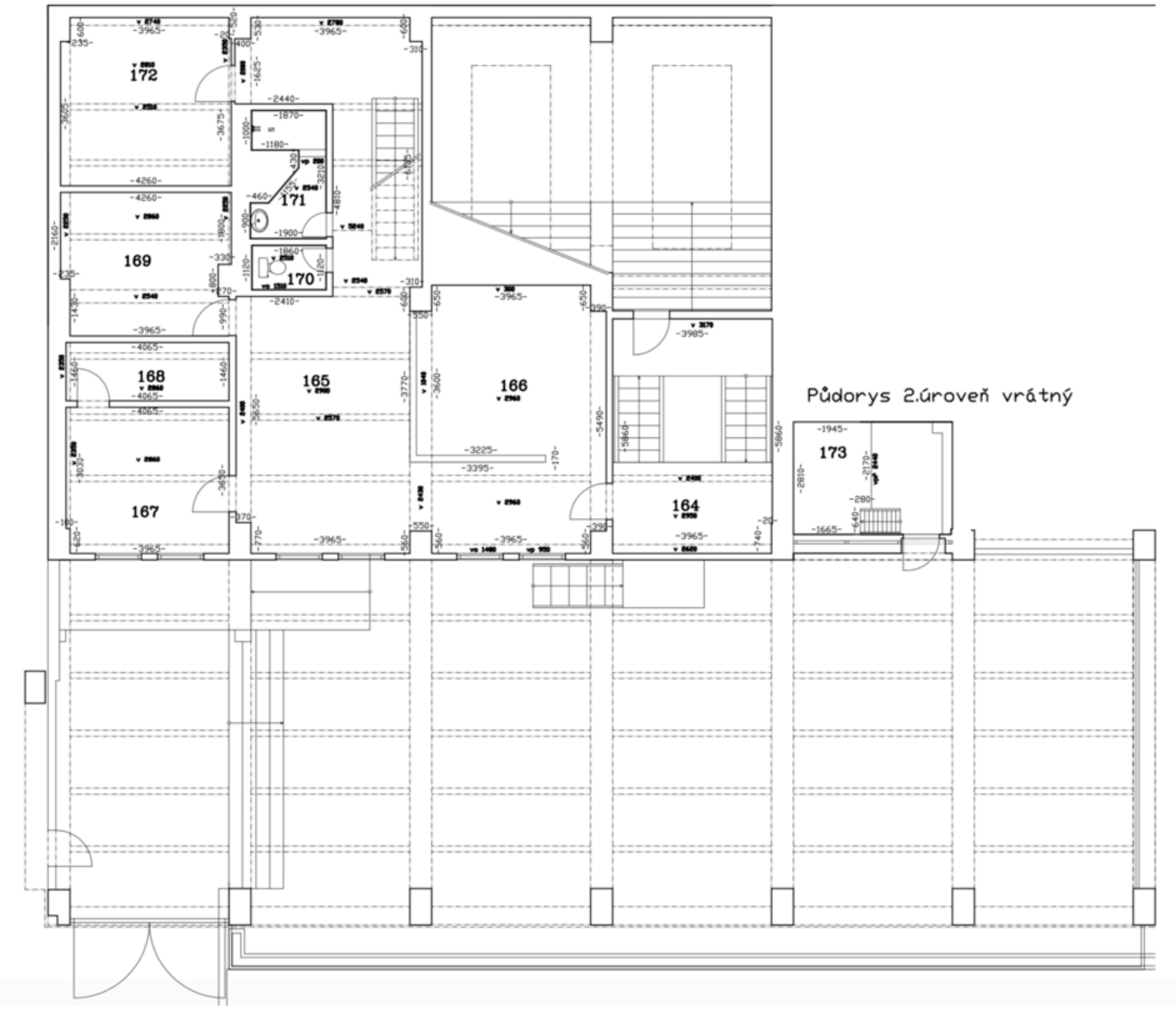
Annexe 1 – North tribune section:



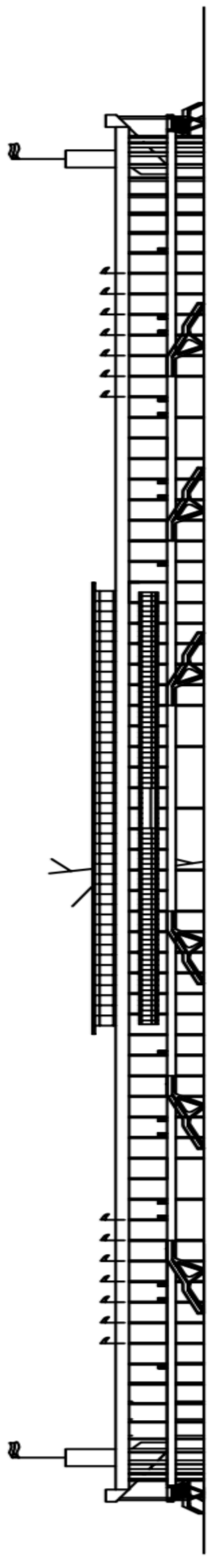
Annexe 2 – South tribune section:

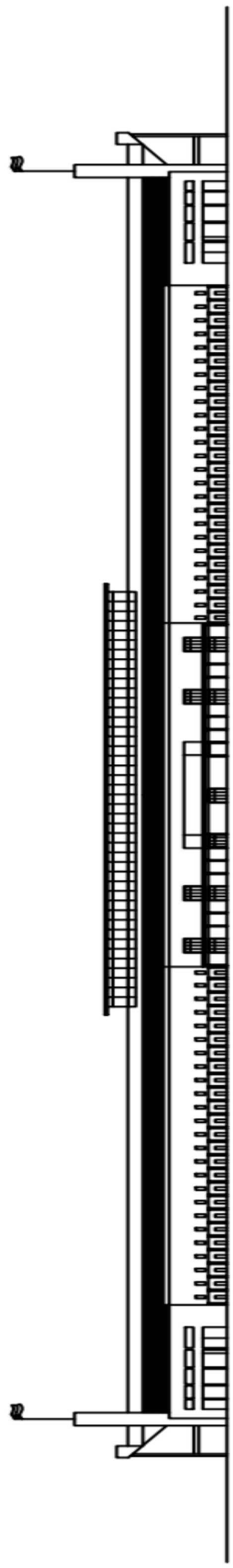


Annexe 3 – Mezzanine in North tribune:

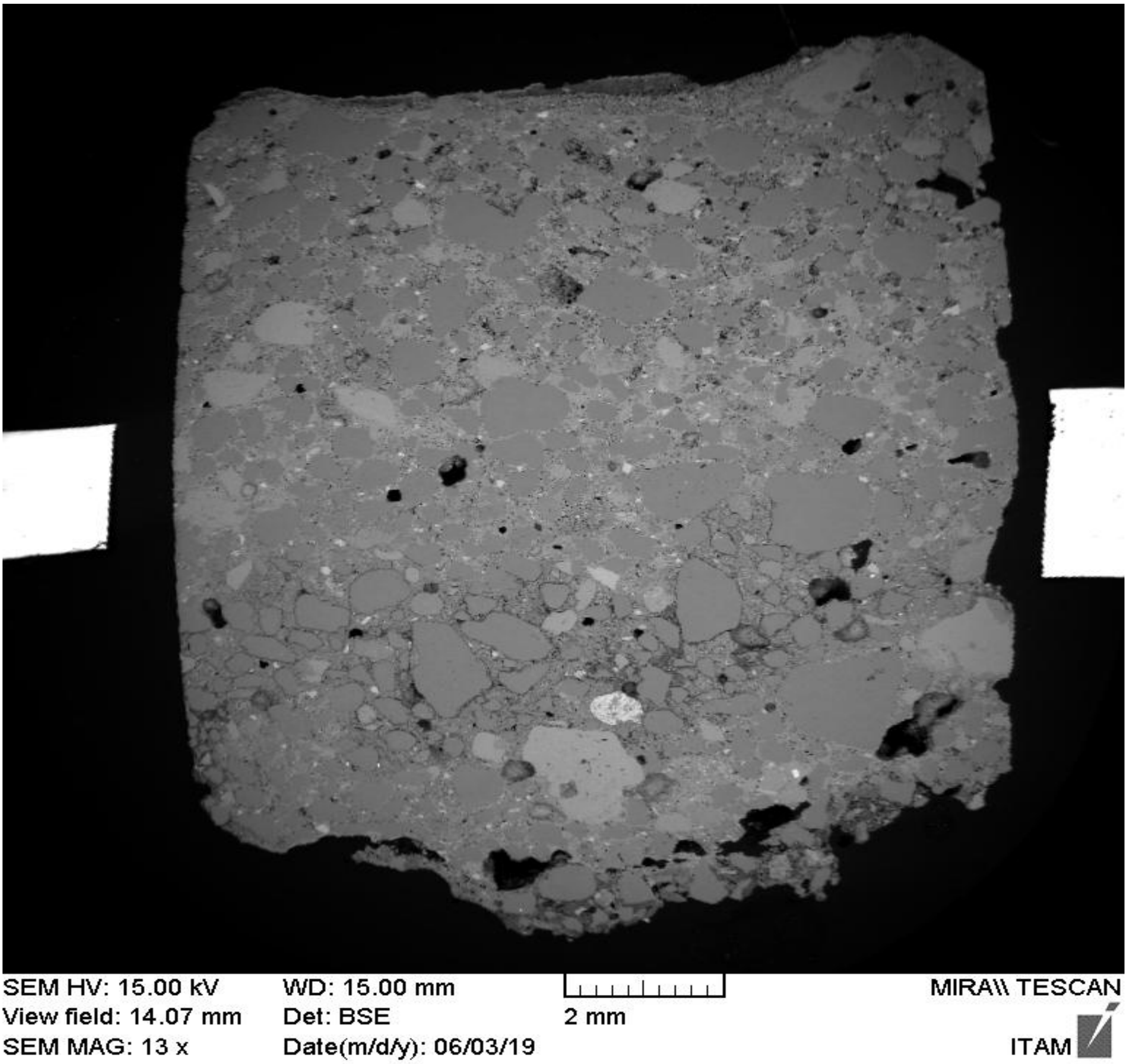


Annexe 4 – East (left) and West (right) tribunes:

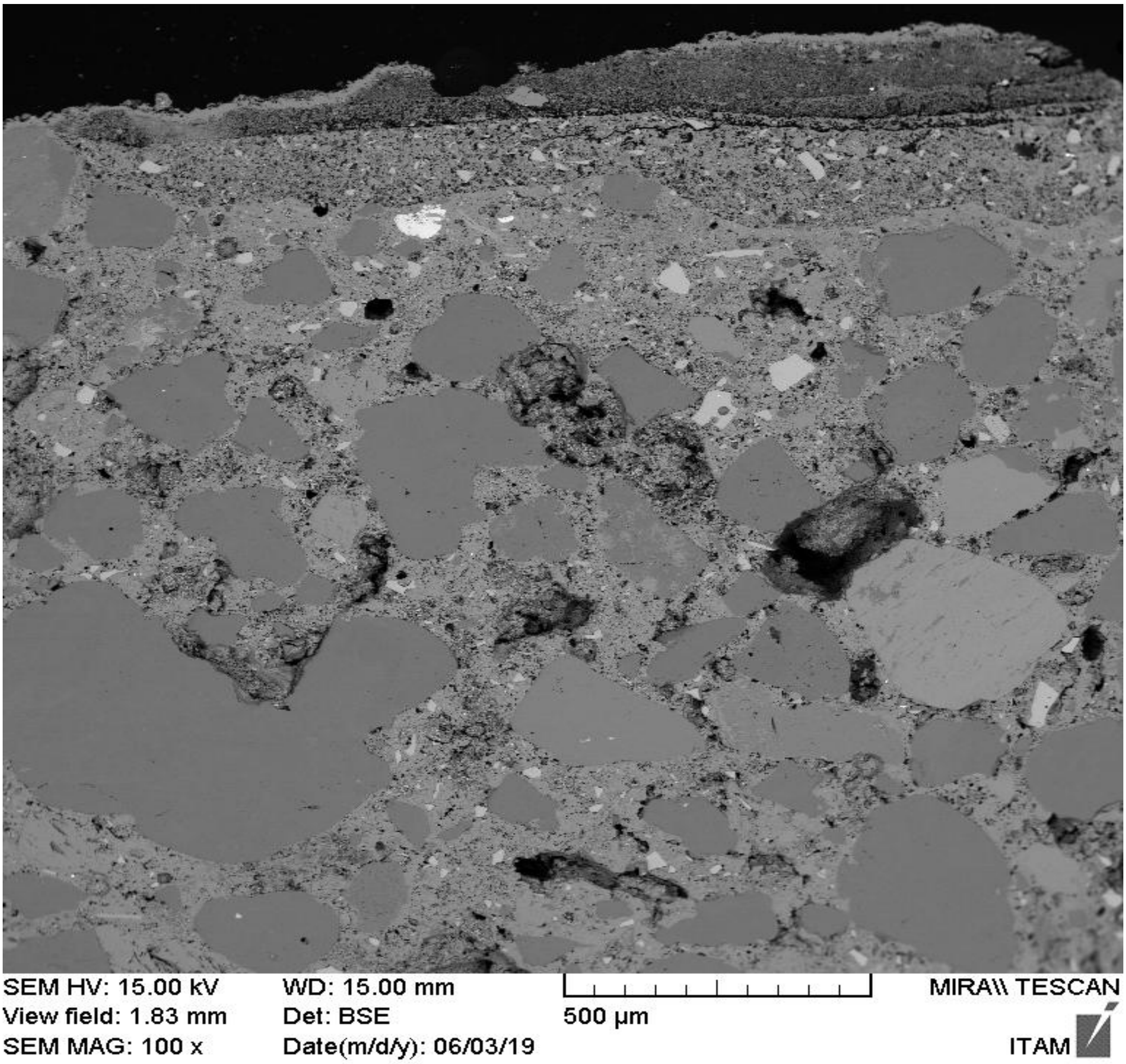




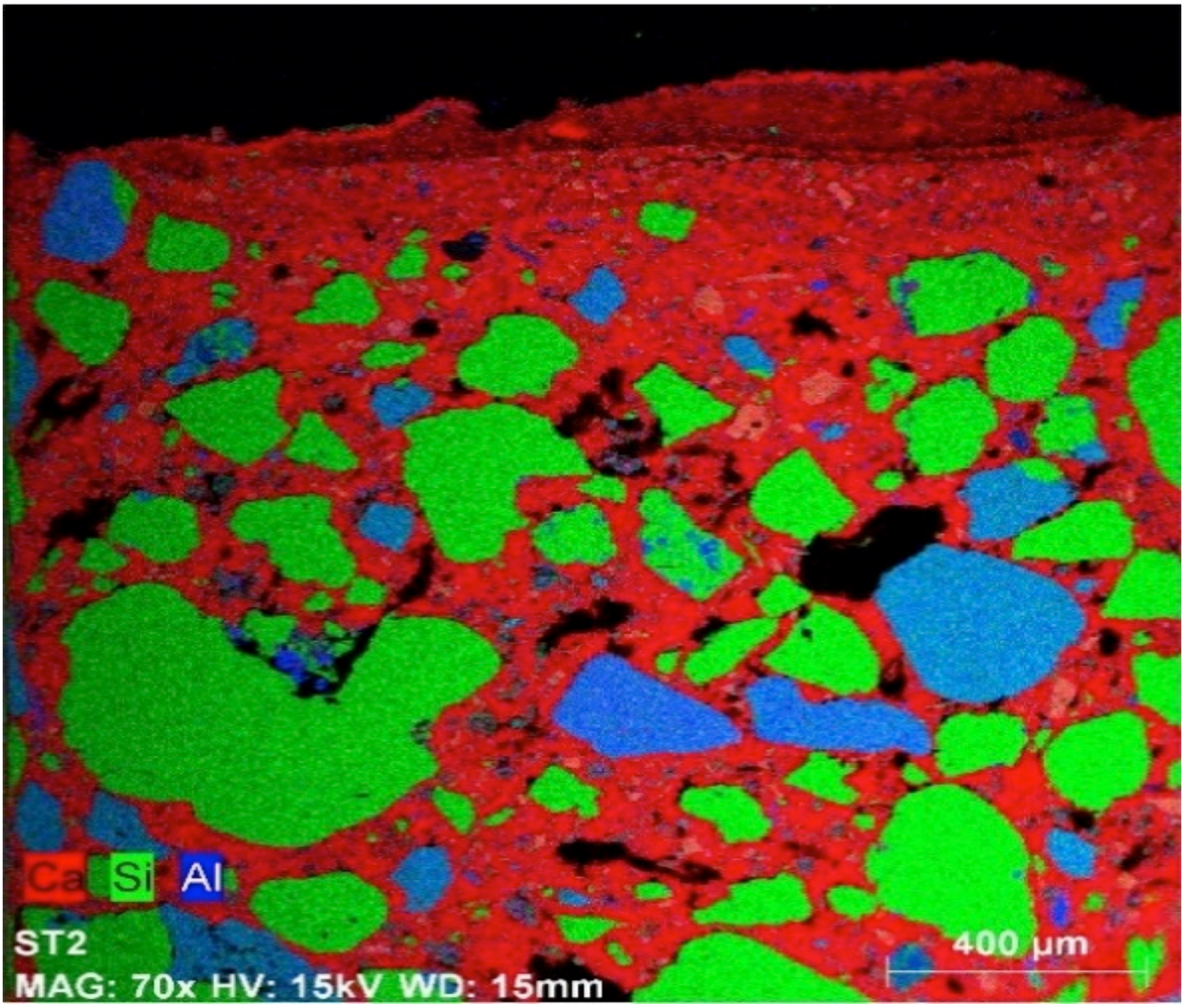
Annexe 5 – Sample ST2:



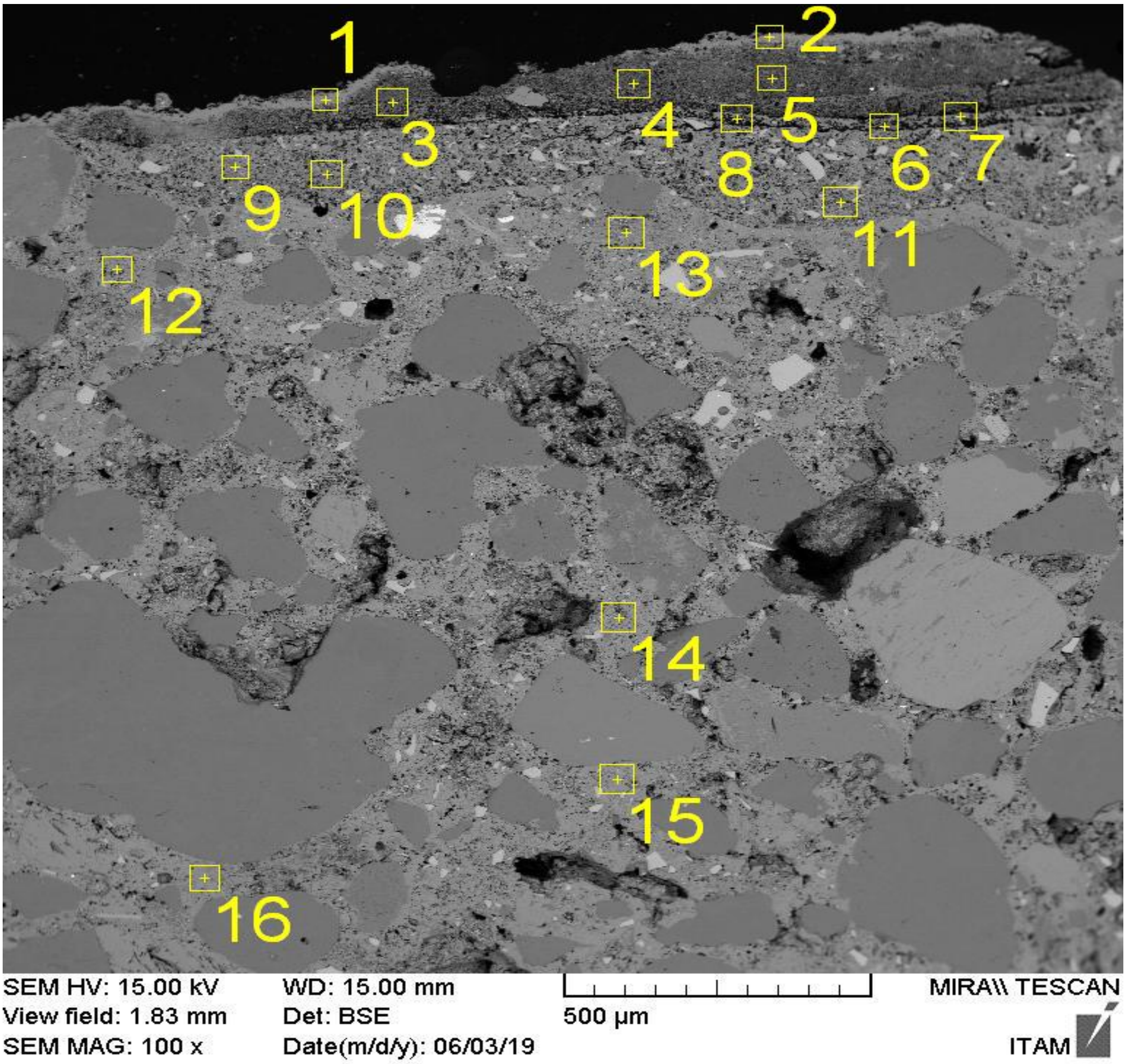
Annexe 6 – Sample ST2 surface:



Annexe 7 – Sample ST2 compounds:

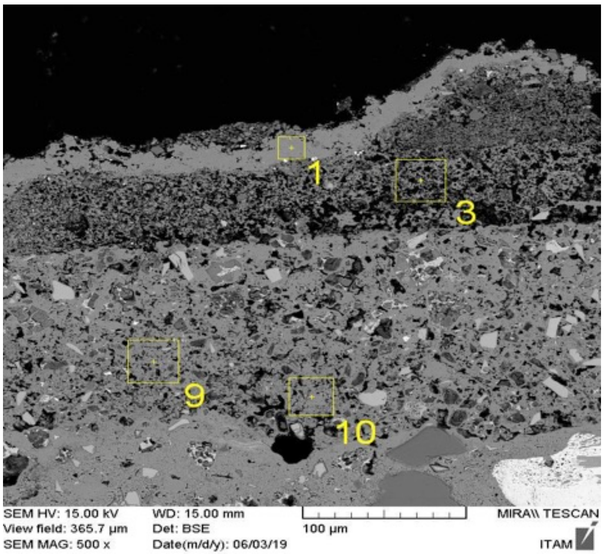


Annexe 8 – Sample ST2 numbered sections:

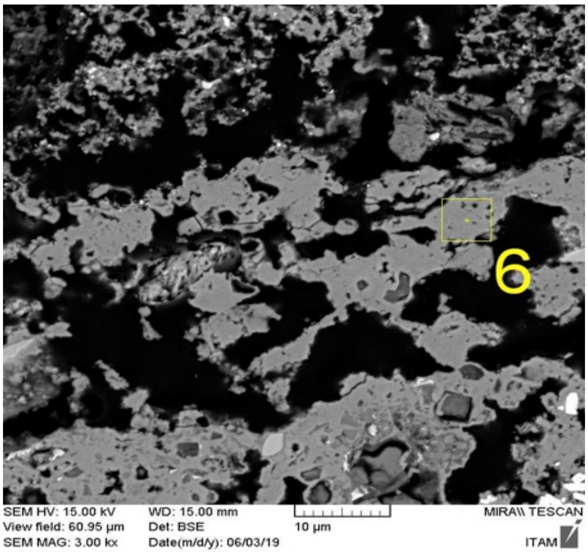


Annexe 9 – Sample ST2 calcium oxide predominance:

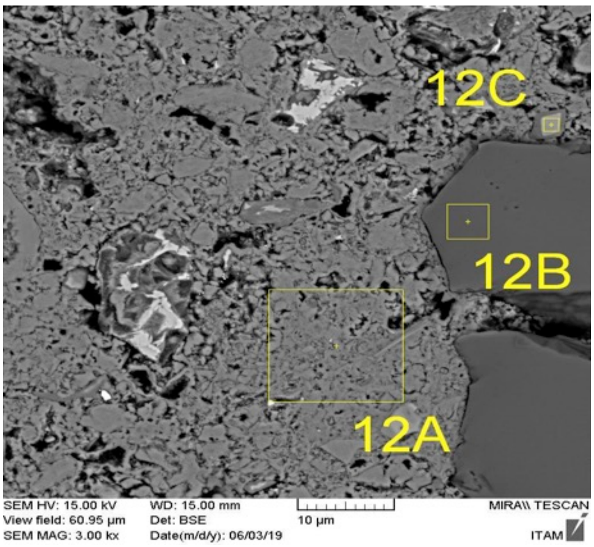
Section 1:



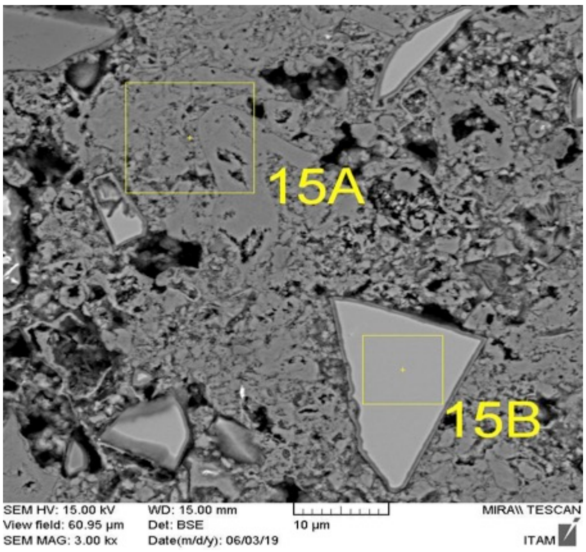
Section 6:



Section 12A:

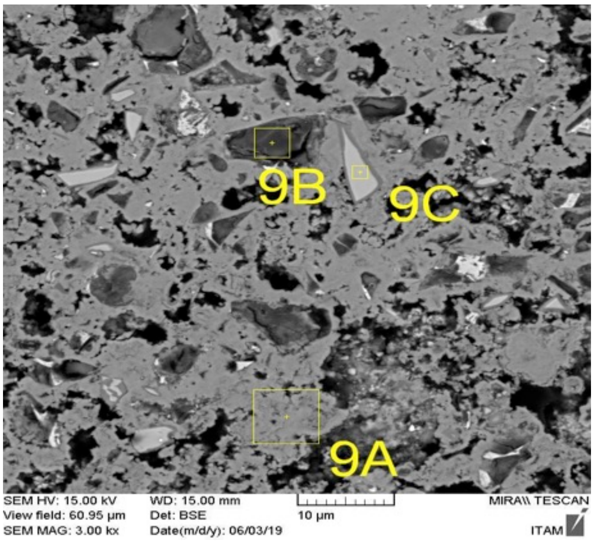


Section 15A:

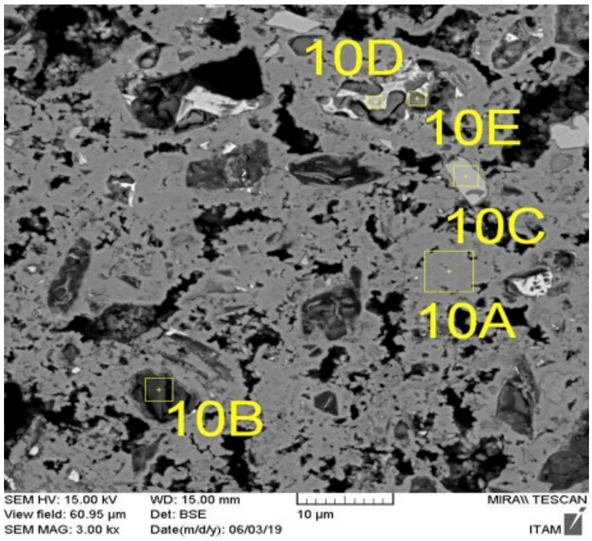


Annexe 10 – Sample ST2 silicum dioxide predominance:

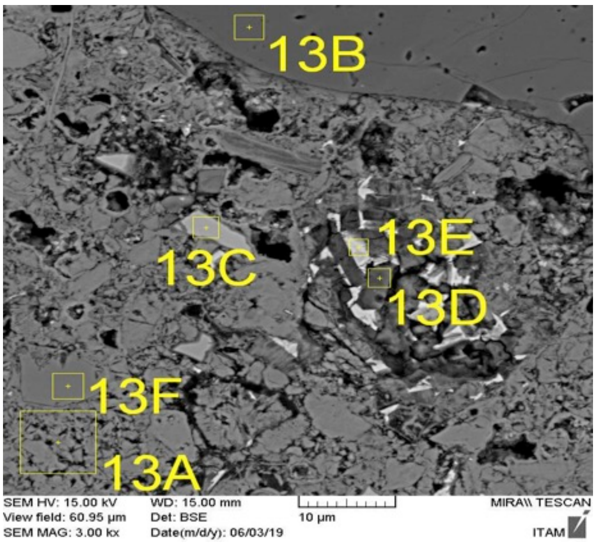
Section 9B:



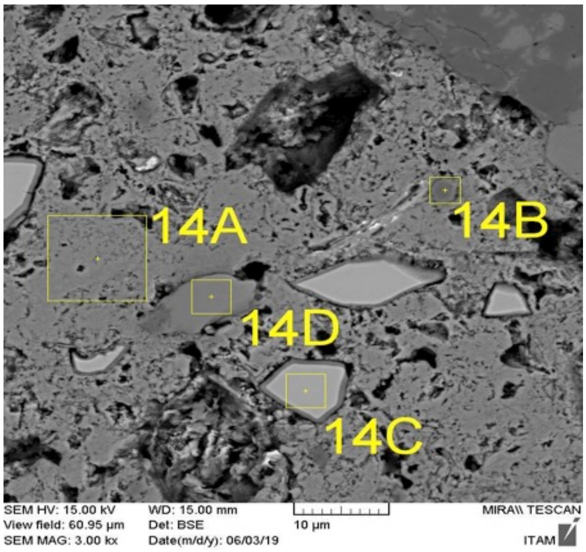
Section 10B:



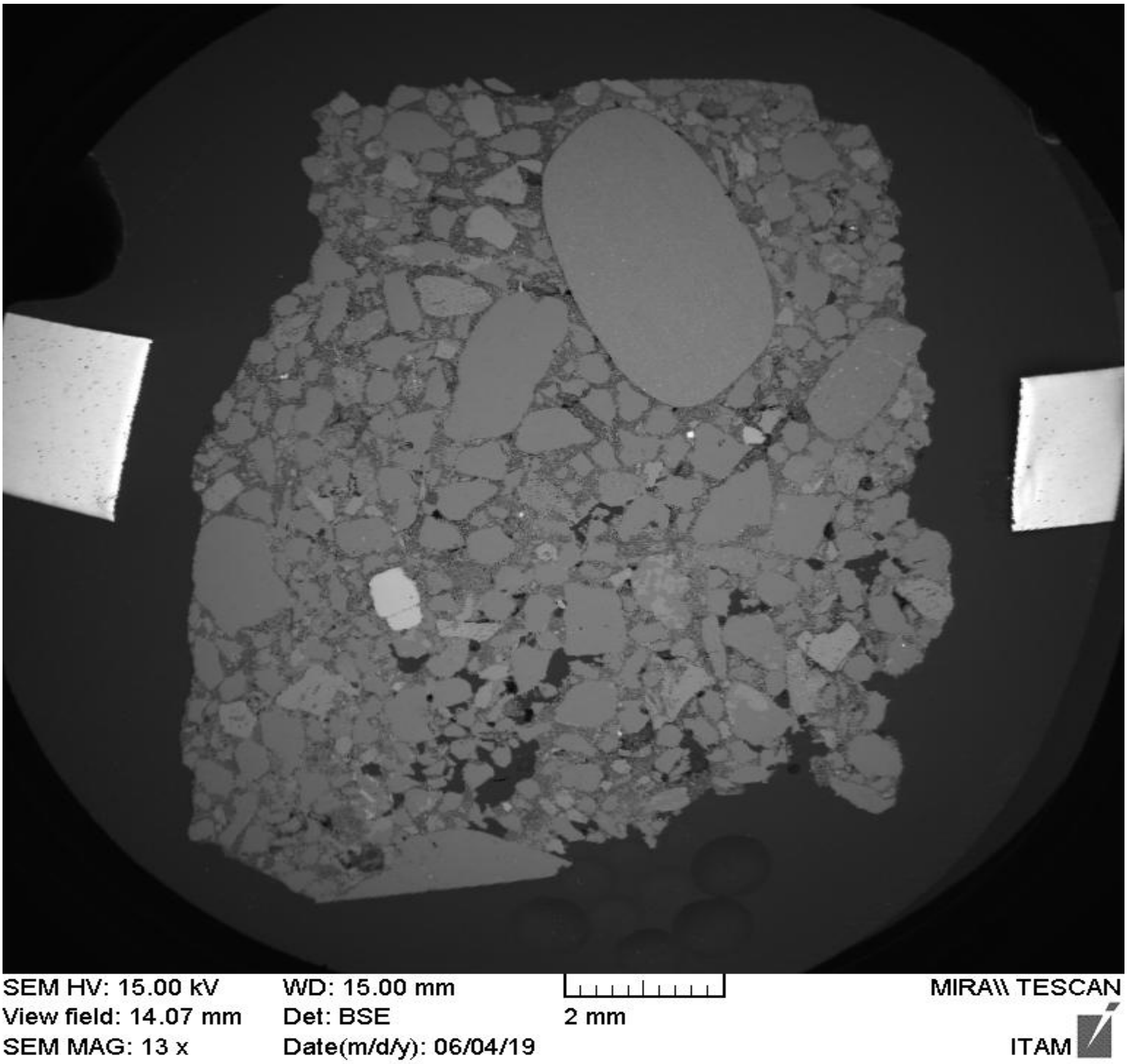
Section 13B:



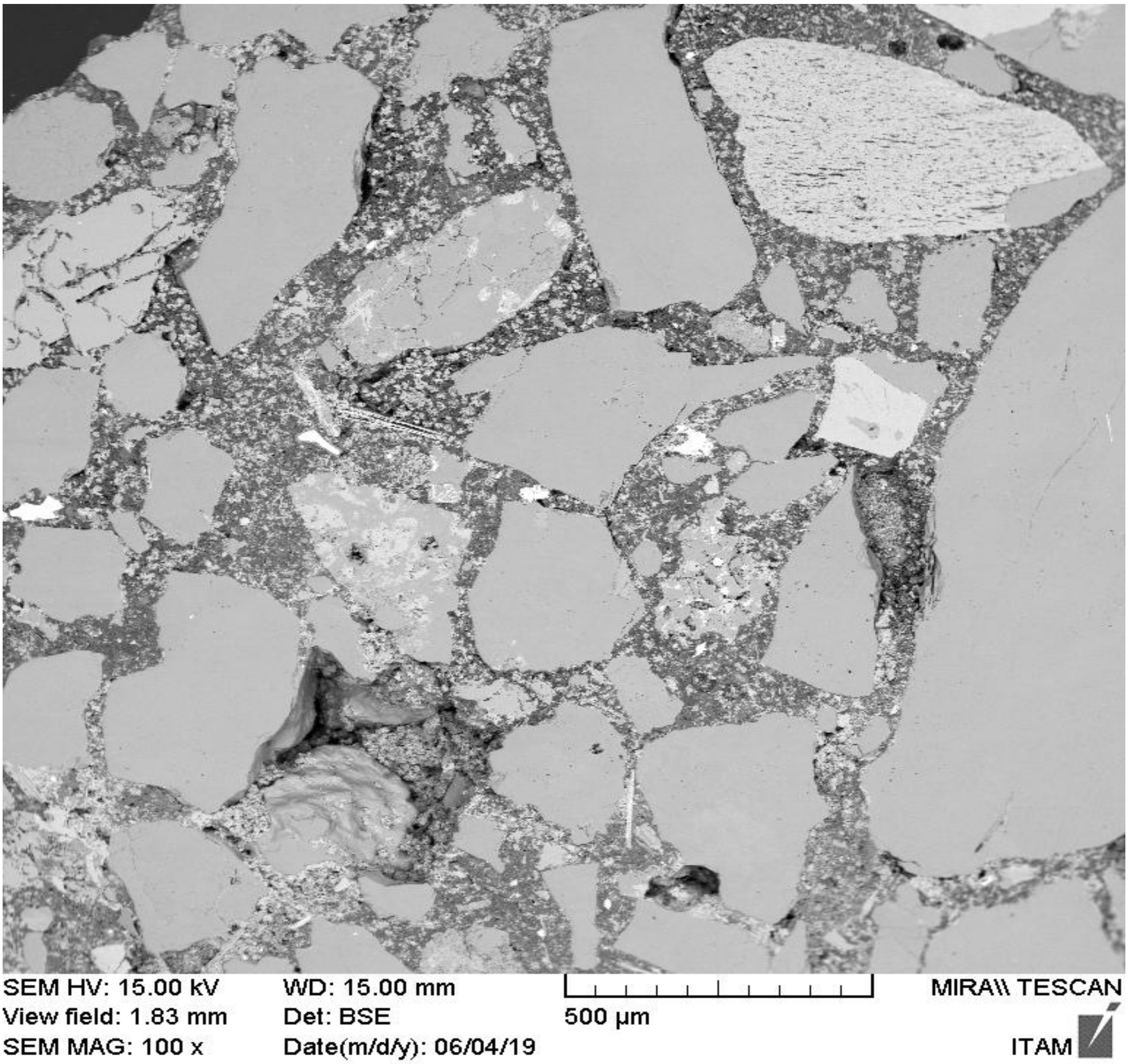
Section 14B/D:



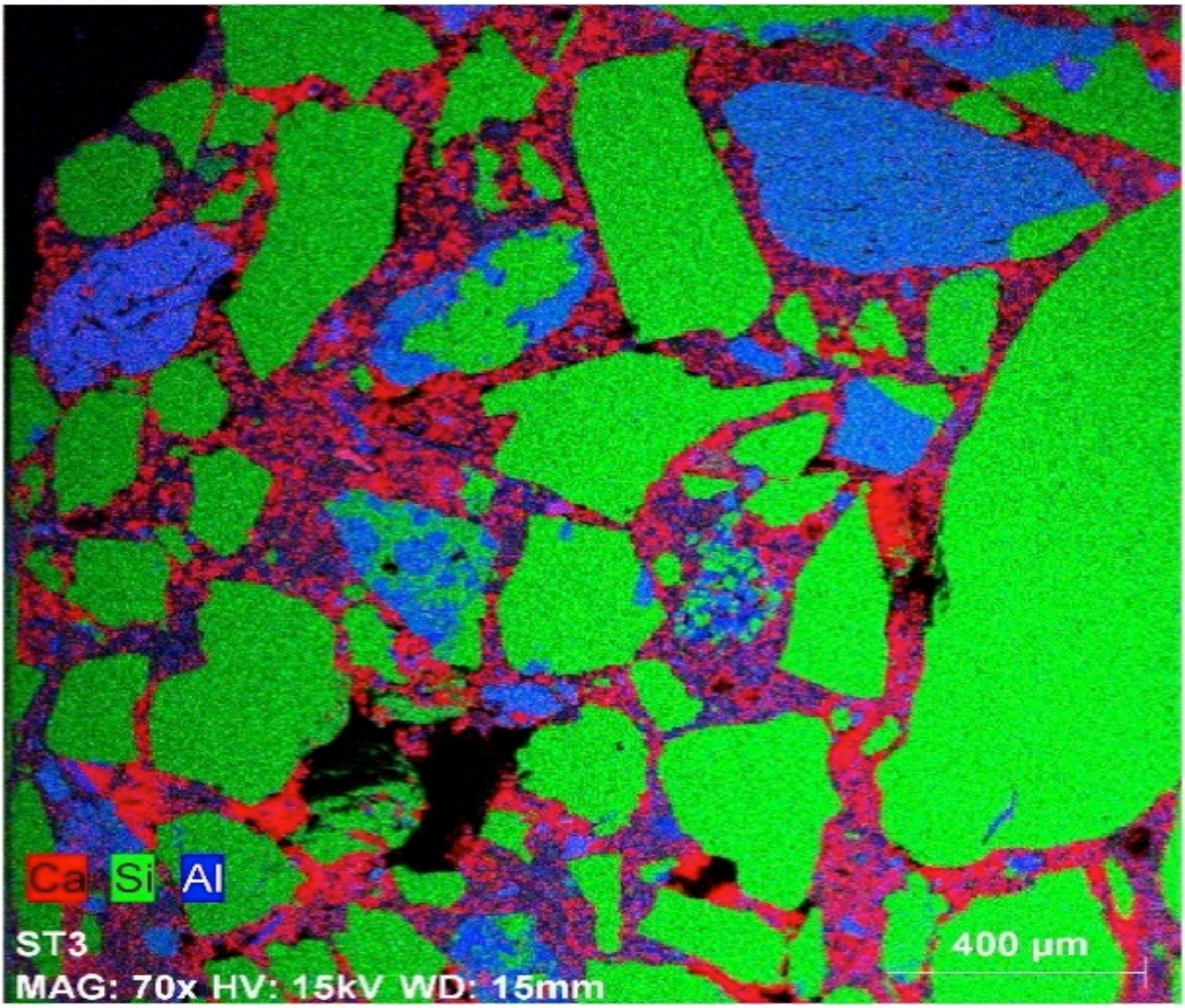
Annexe 11 – Sample ST3:



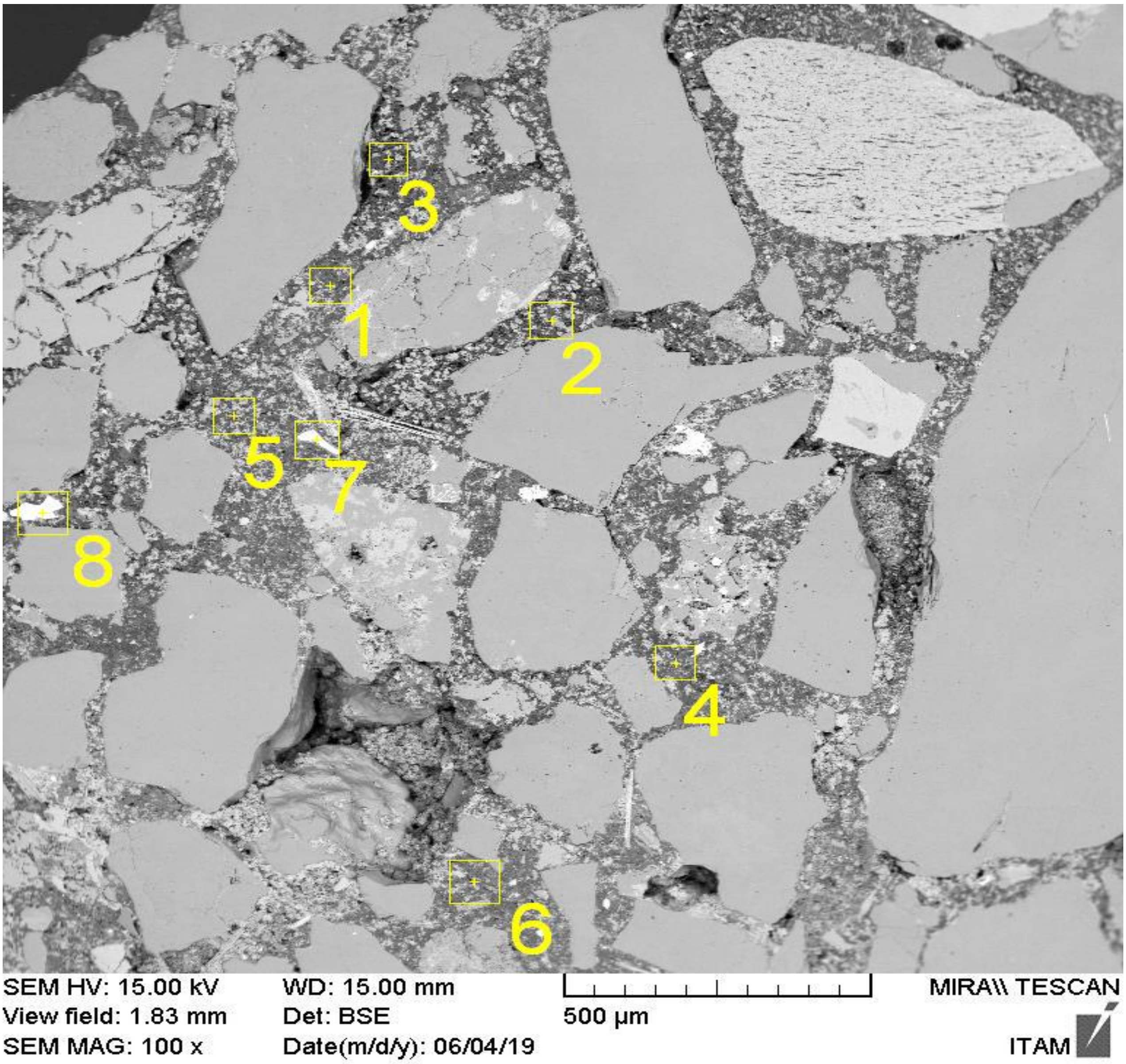
Annexe 12 – Sample ST3 surface:



Annexe 13 – Sample ST3 compounds:

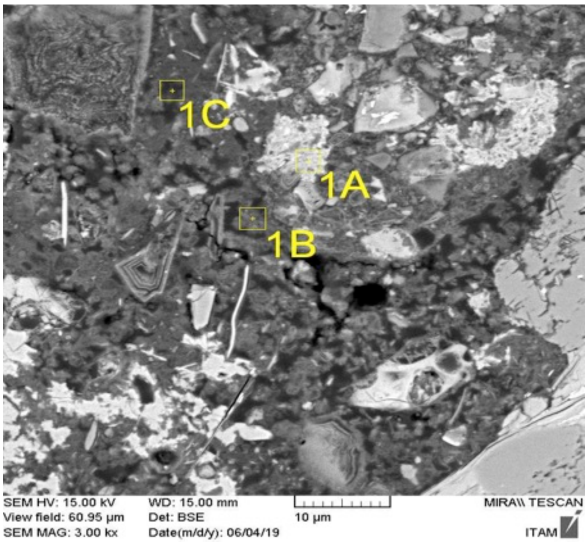


Annexe 14 – Sample ST3 numbered sections:

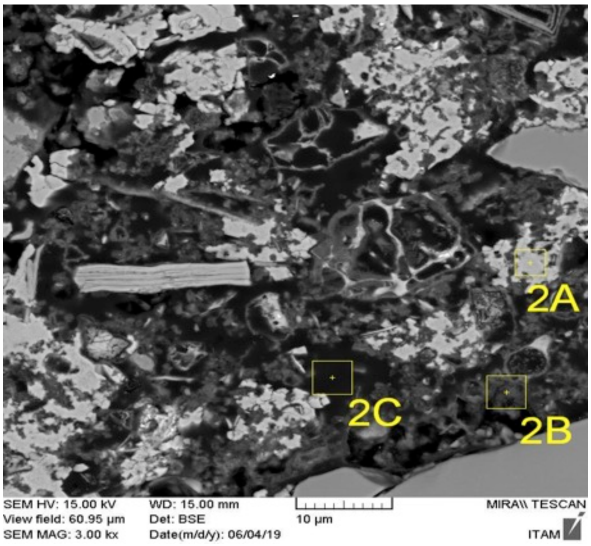


Annexe 15 – Sample ST3 calcium oxide predominance:

Section 1A:



Section 2A:



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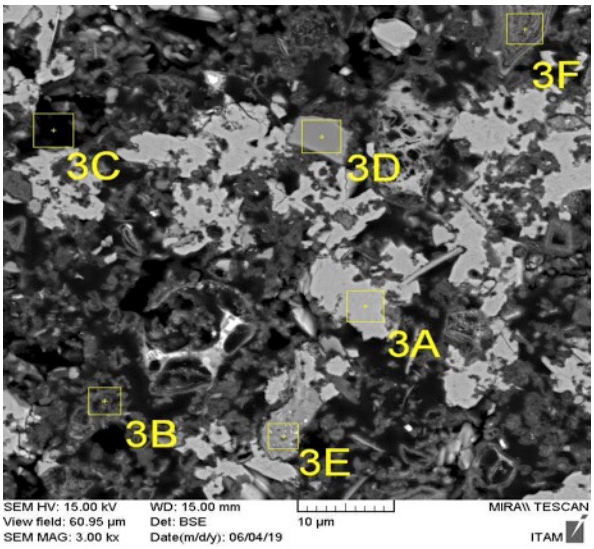
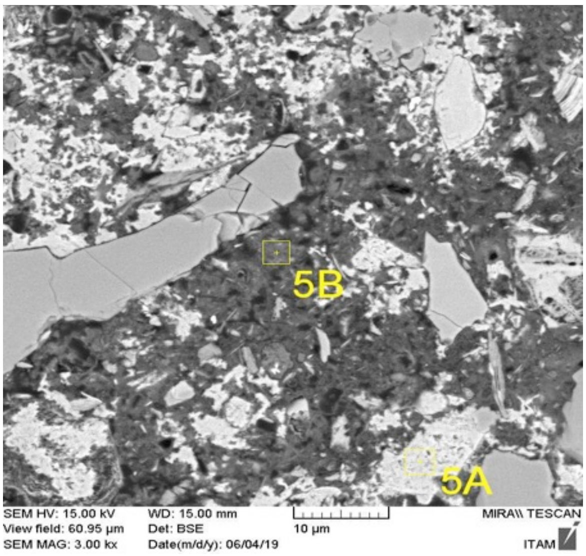
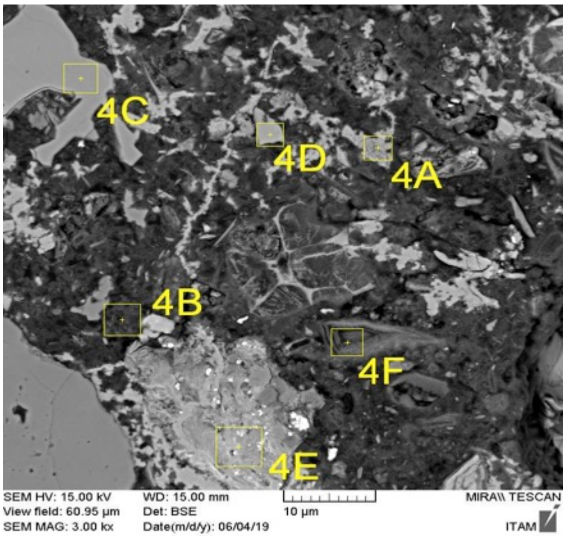


Section 5A:

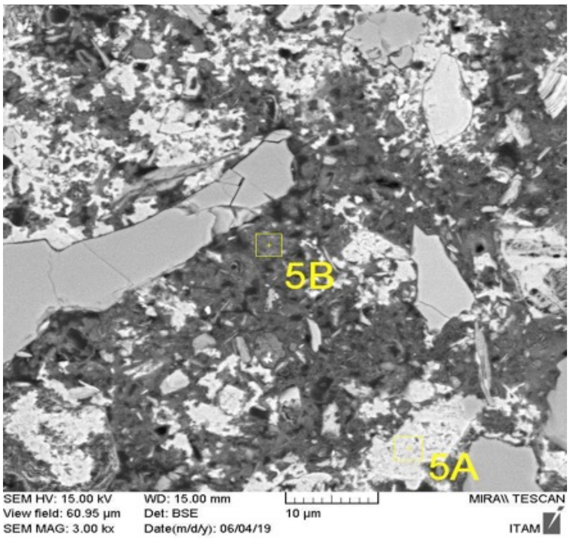


Annexe 16 – Sample ST3 silicum dioxide predominance:

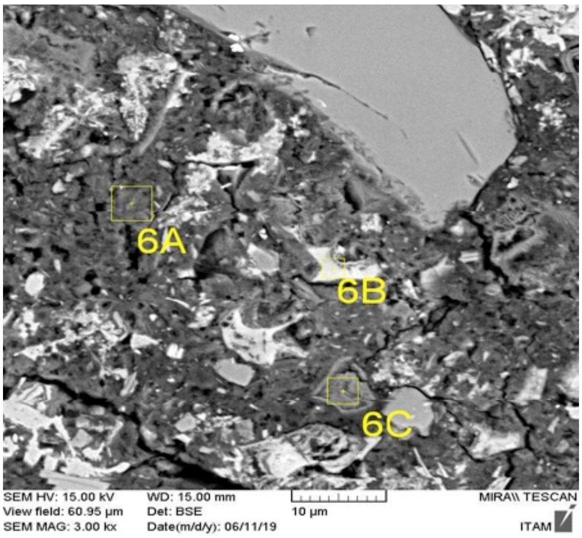
Section 4A/B/C/D:



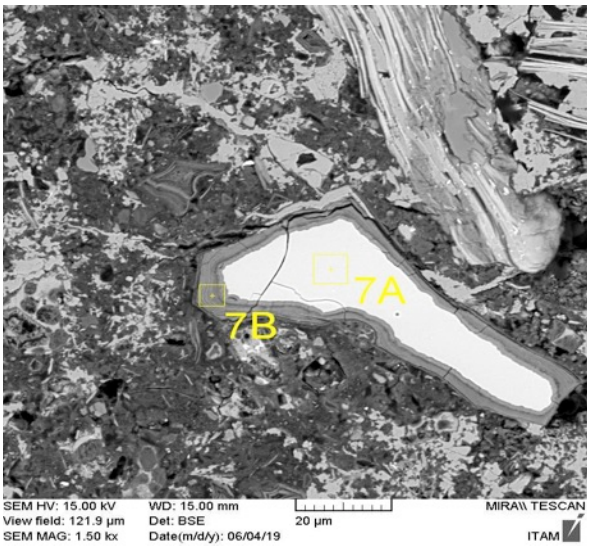
Section 5B:



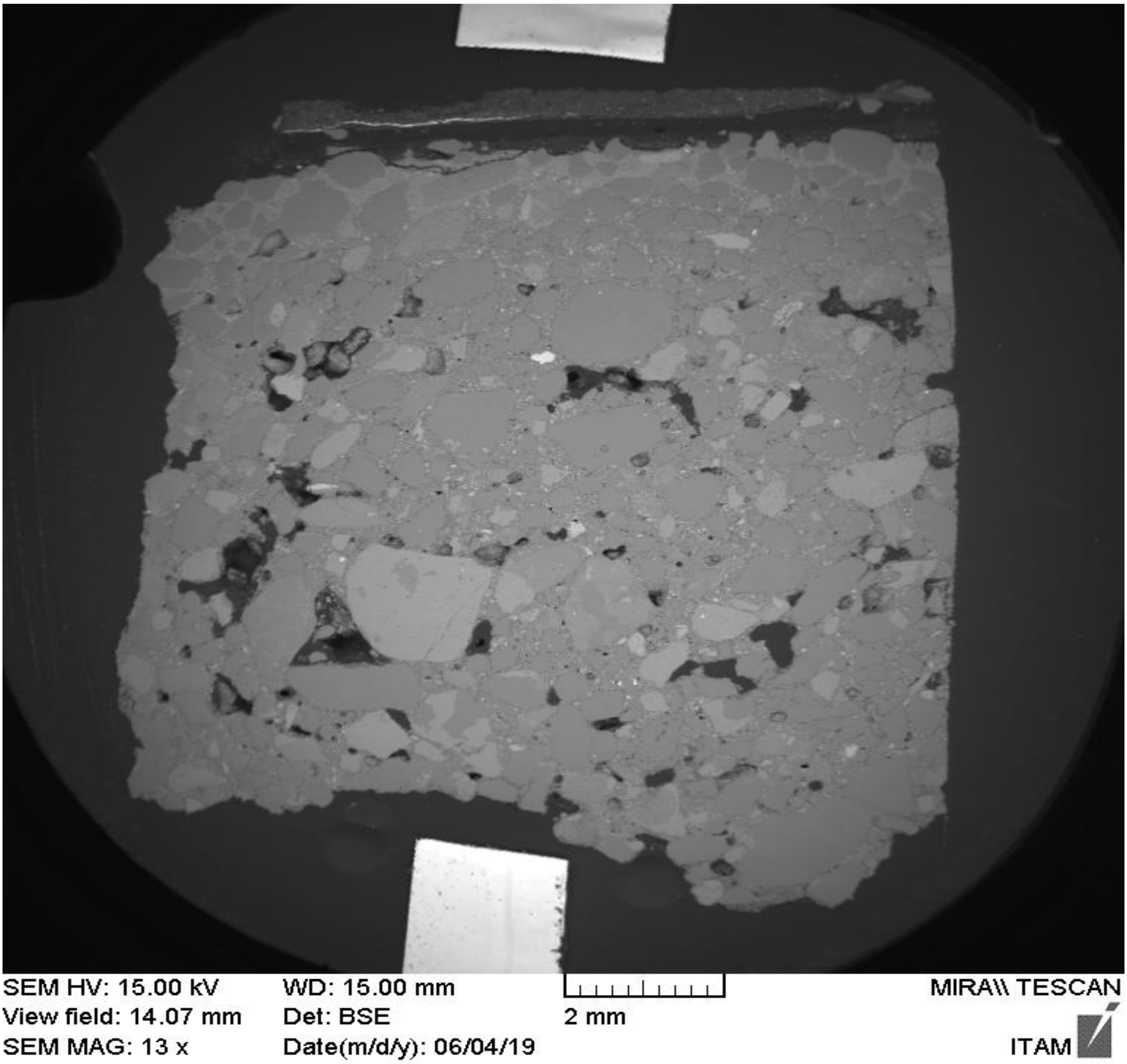
Section 6A/B:



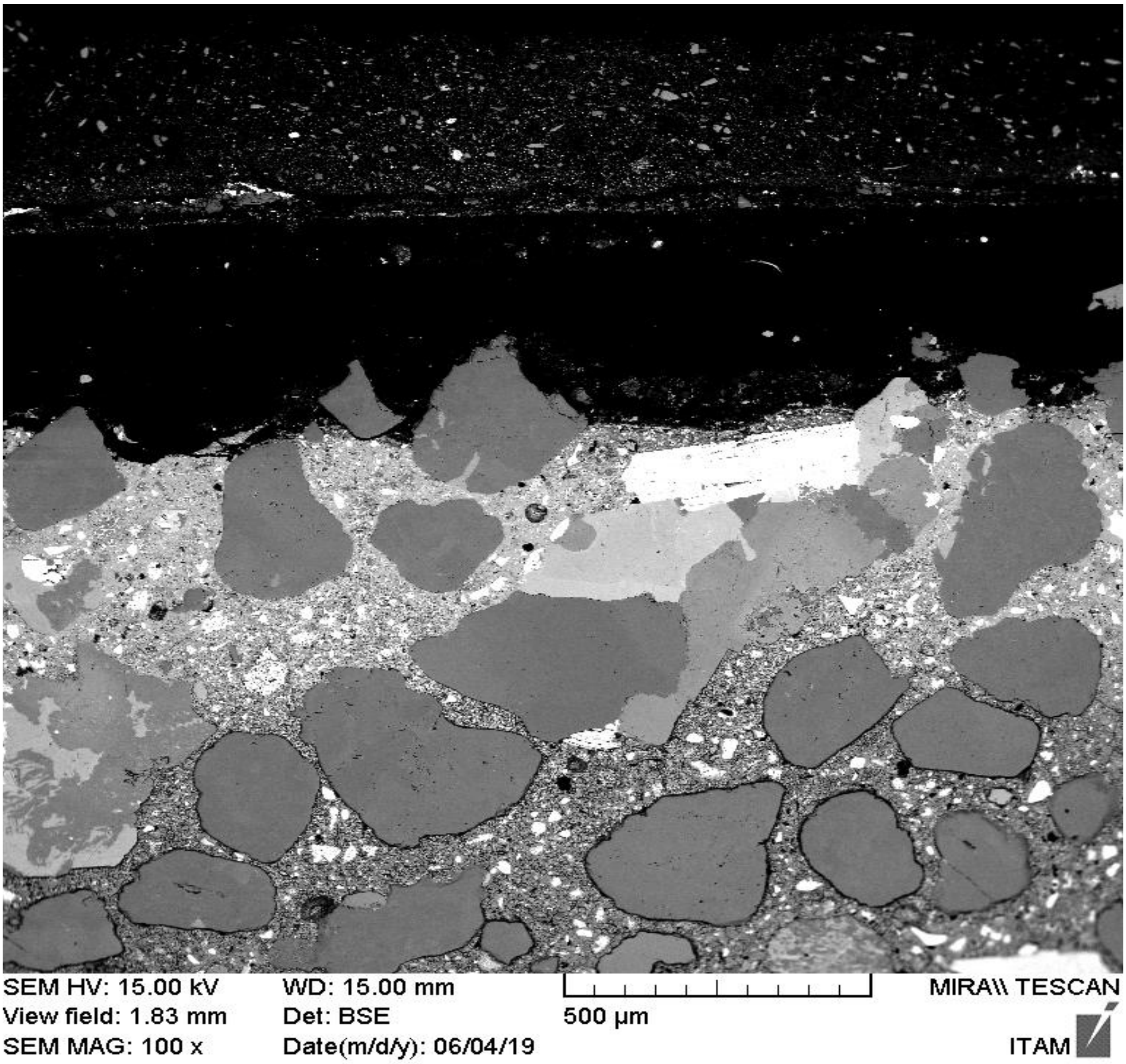
Section 7B:



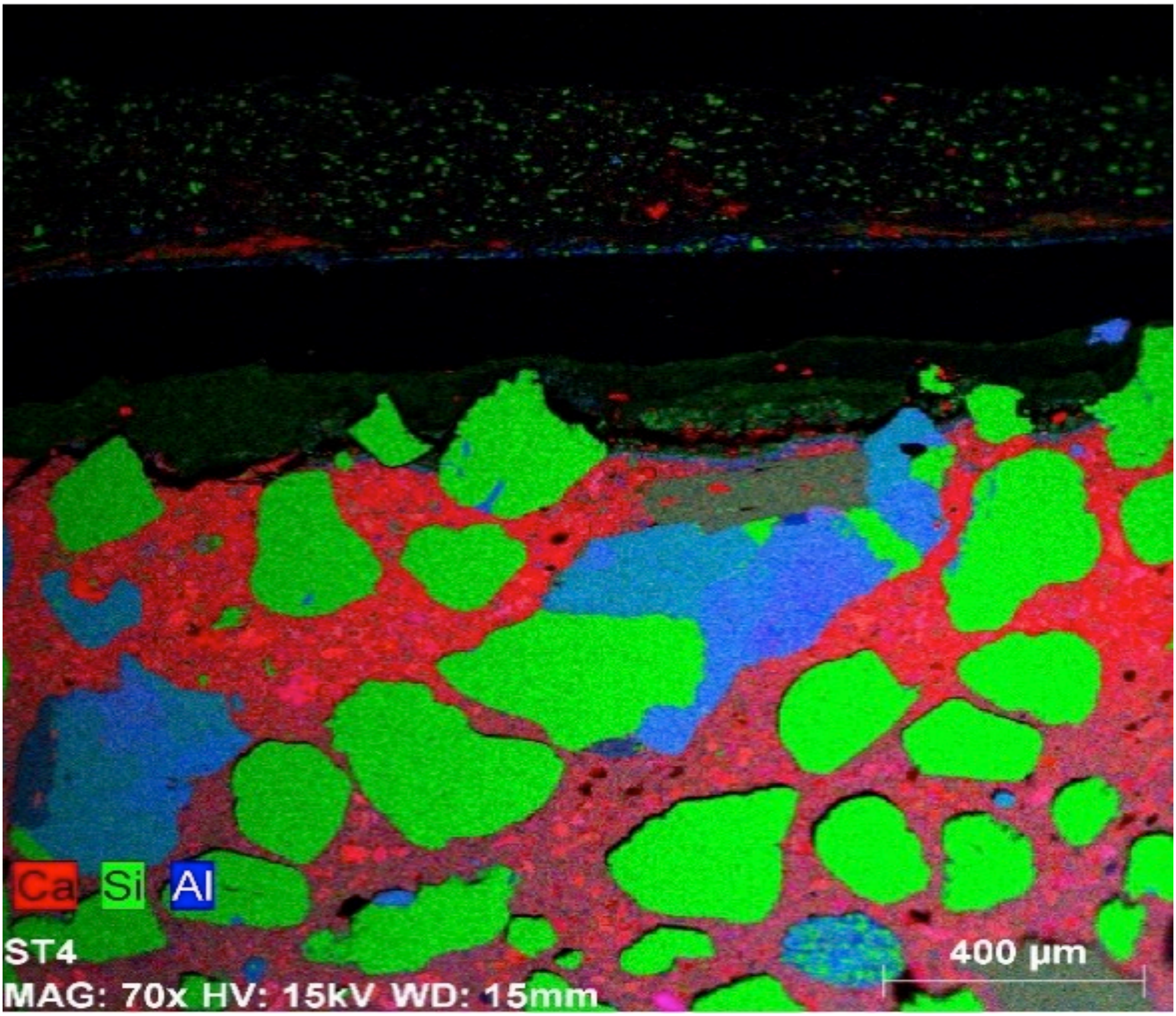
Annexe 17 – Sample ST4:



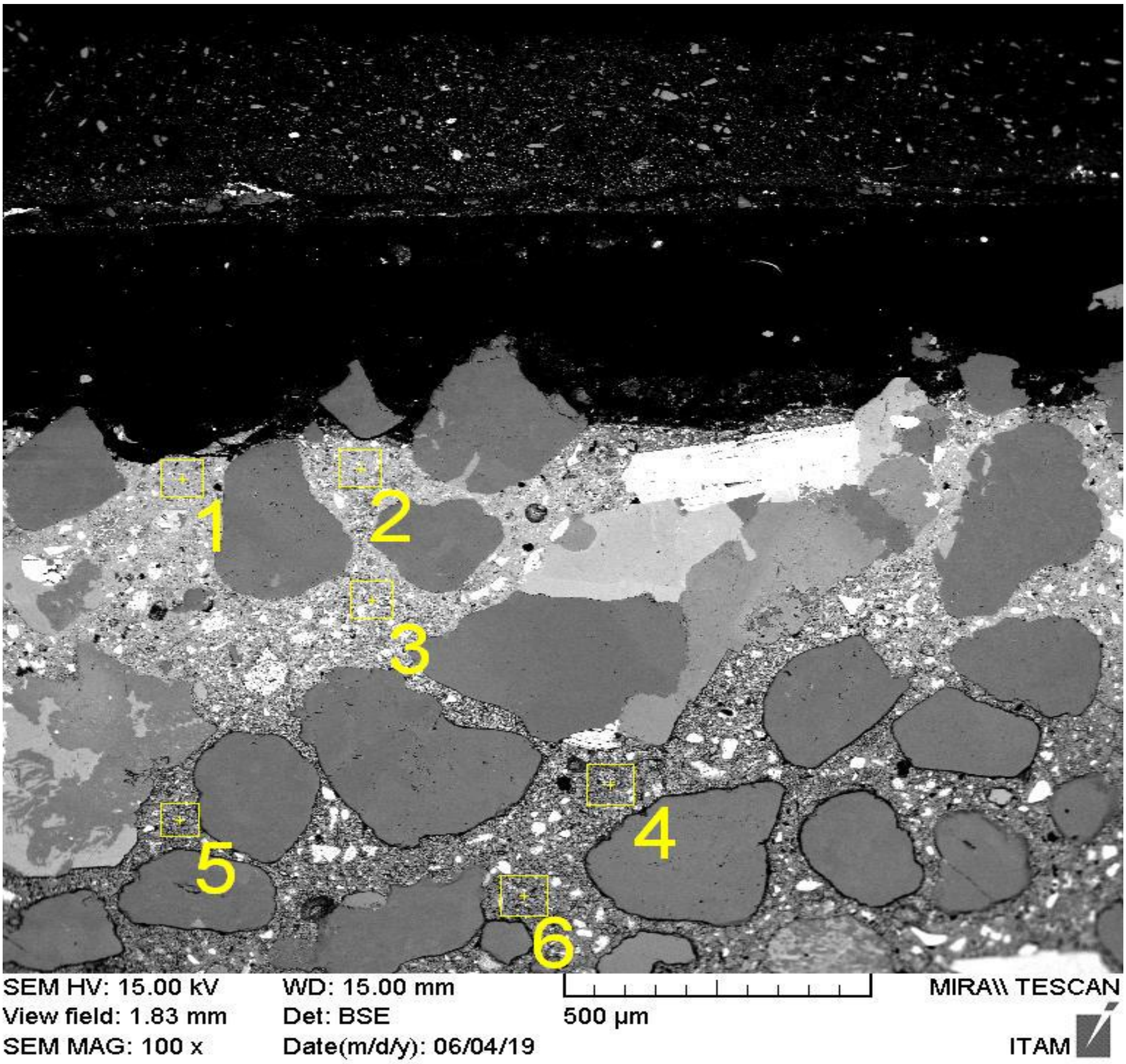
Annexe 18 – Sample ST4 surface:



Annexe 19 – Sample ST4 compounds:

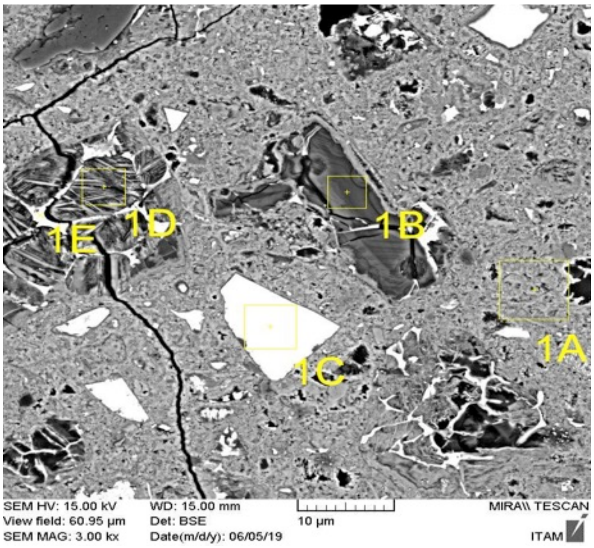


Annexe 20 – Sample ST4 numbered sections:

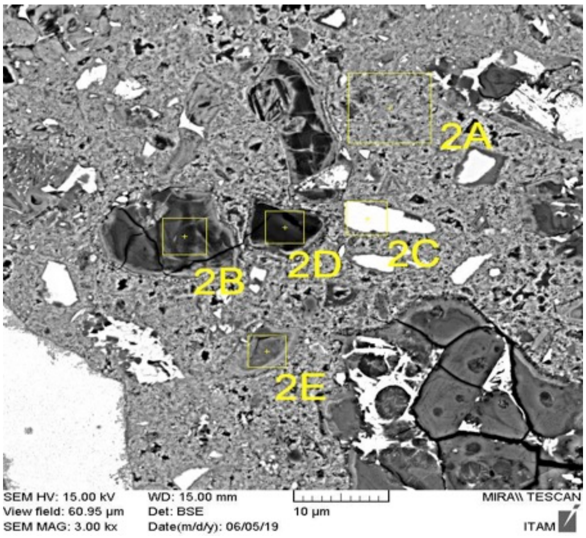


Annexe 21 – Sample ST4 calcium oxide predominance:

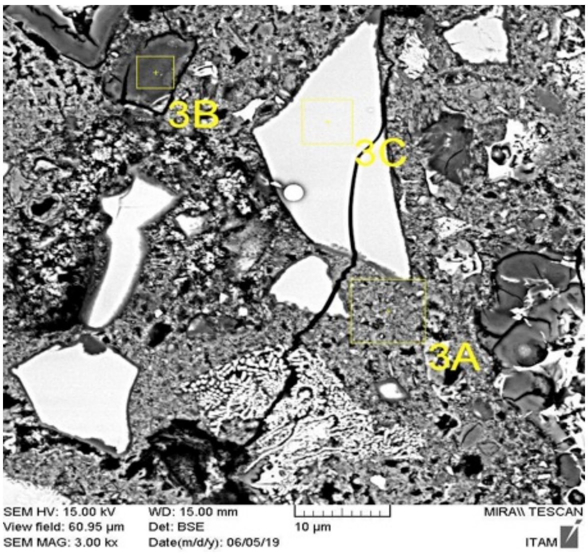
Section 1A:



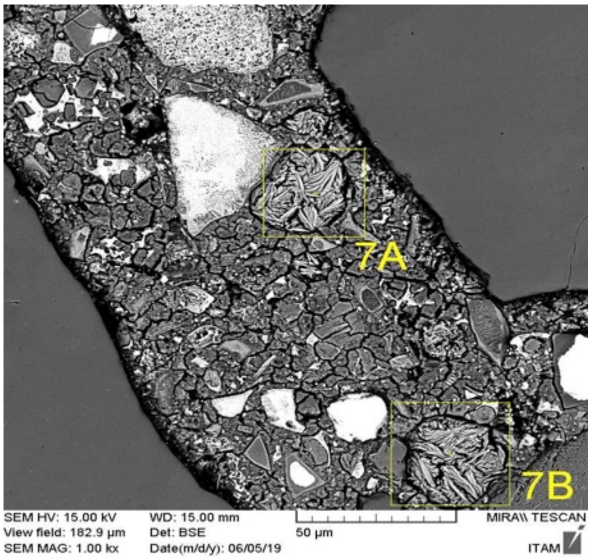
Section 2A:



Section 3A:

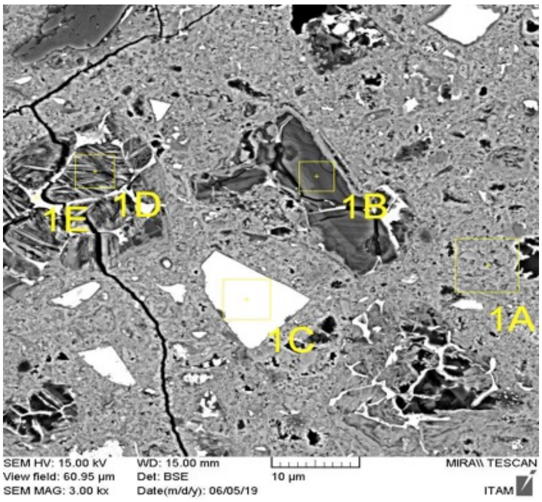


Section 7B:

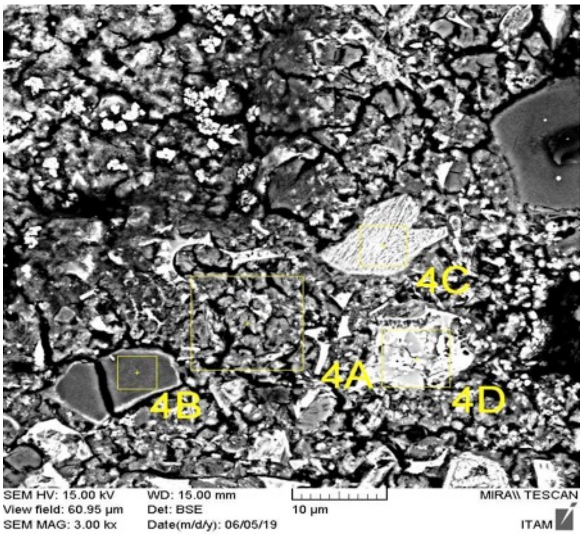


Annexe 22 – Sample ST4 silicum dioxide predominance:

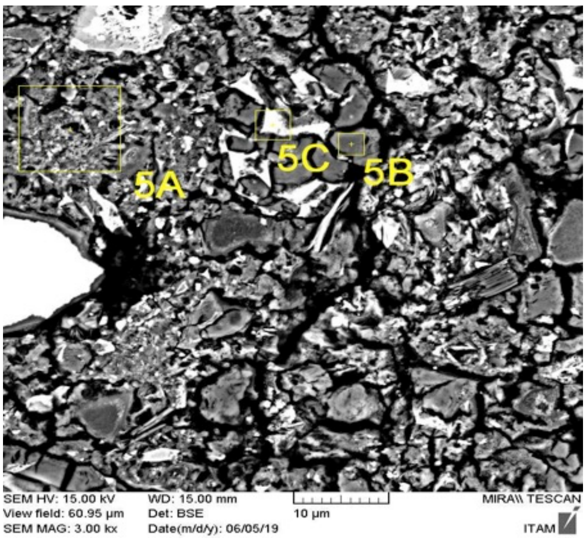
Section 1B/D:



Section 4A/B:



Section 5B:



Section 6B: