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Recovery procedures for foundation elements with alkali/aggregate reaction problems. Documental research

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ABSTRACT
The alkali-aggregate reaction (AAR) is a problem that has affected numerous foundations. This study, through an investigation of fifty foundations, seeks to create a profile of the recovery processes through consultations with inspection companies that have carried out recoveries in the city of Recife and neighboring areas. The methodology consisted on the application of a survey with seventeen questions. The results obtained made possible to establish similarities in the foundations affected, the diagnoses, processes applied during recovery, advances in materials, conditioning factors for the use of the reinforcement, and costs, and also identified the foundations where an inspection window was left for future checks. The results conclude with an evaluation of the treatments for foundations affected by AAR.
Keywords: foundations; alkali-aggregate reaction; diagnosis; procedures; recovery.

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Procedimentos de recuperações em elementos de fundações por problemas de reação álcali agregado. Investigação documental

RESUMO

A Reação Álcali Agregado (RAA) atingiu muitas fundações e observou-se a importância de realizar uma verificação nos procedimentos de recuperações, compreendendo uma investigação em cinquenta fundações, objetivando traçar um perfil dos processos de recuperações através de consulta no acervo de empresas fiscalizadoras ou executoras de recuperações na cidade de Recife e cidades vizinhas. A metodologia consistiu na aplicação de um questionário com dezessete perguntas. Esses resultados possibilitaram estabelecer as semelhanças das fundações afetadas, o diagnóstico, processos aplicados na recuperação, os avanços dos materiais, fatores condicionantes para utilização da armadura, os custos, e possibilitaram a identificar as fundações que deixaram uma janela de inspeção para posteriores verificações. Concluindo-se com os resultados uma avaliação dos tratamentos nas fundações acometidas pela reação RAA.

Palavras-chave: fundações; reação álcali agregado, diagnóstico, procedimentos, recuperações.

Procedimientos de recuperación en fundaciones por problemas de reacción álcali/agregado. Investigación documental

RESUMEN

La reacción álcali/agregado (AAR) ha afectado muchas cimentaciones lo cual señala la importancia de realizar una verificación de los procedimientos de recuperación, la cual se realizó en cincuenta cimentaciones. El objetivo fue construir un perfil de los procesos de recuperación a través de una consulta con empresas de inspección o ejecutores de recuperaciones en la ciudad de Recife y ciudades vecinas. Para ello se aplicó en forma metodológica un cuestionario con diecisiete preguntas. Estos resultados permitieron establecer las similitudes de las cimentaciones afectadas, el diagnóstico, los procesos aplicados en la recuperación, los avances en materiales, los condicionantes para el uso de la armadura, los costos, y permitieron identificar las cimentaciones que dejaron una ventana de inspección para controles adicionales. El resultado fue una evaluación de los tratamientos en las bases afectadas por la reacción química AAR.

Palabras clave: fundaciones; reacción alcalina agregada; diagnóstico; procedimientos; recuperaciones.

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1. INTRODUCTION

In the early 1940s, the scientific community was faced with a "disease" affecting large concrete structures. It was a slow and progressive reaction that developed through a chemical process between alkaline hydroxides, found in the existing solutions in the pores of the concrete paste, and reactive minerals found in certain types of aggregates, in the presence of water. The alkali-aggregate reaction, better known as AAR, is a deleterious long-duration chemical reaction, which can result in the formation of an expansive gel, forming cracks and chips in concrete, leading to a loss of durability, among other properties.
In Brazil, the pioneering scholars who studied this reaction were Heraldo de Souza Gitahy and Murilo Dondici Ruiz. In 1963, through the Institute for Technological Studies in São Paulo (IPT), they reported on the AAR reaction, its behavior, the materials involved, as well as mitigating actions, aimed at the Urupungá Power Plants.
Despite all of the scientific discoveries and the firm intention to improve and consolidate studies on concrete, problems related to structural aging, linked to a lack of maintenance and the incipient knowledge regarding some pathologies, such as the alkali-aggregate reaction (AAR), responsible for high recovery costs, many uncertainties about the results and durability of these interventions remain.
The existence of the alkali-aggregate reaction in building projects was verified in the Recife Metropolitan Region (RMR) in Pernambuco for the first time, because of the interest generated in inspecting the foundations of several residential buildings, following the collapse of the Areia Branca building in 2004. It should be clarified that the causes of the collapse of the Areia Branca were properly investigated and nothing was found to indicate AAR as the cause of the incident. However, foundation inspections of several other buildings in that region made possible to verify the existence of many cases of cracked concrete in pile caps and footings. The accurate analysis of these occurrences by experts, based on concrete samples extracted from the foundation elements, showed that the cracking was indeed caused by the alkali-aggregate reaction, with laboratories of the Brazilian Portland Cement Association (ABCP) having studied more than 60 cases (Battagin, 2016).
According to Otoch (2016), the occurrence of expansion caused by AAR was, until recently, mainly an issue with large constructions, such as dams or parts of hydroelectric plants. More recently, at the end of 2014 and throughout 2015, several cases of AAR were found in the Recife/PE area, mainly in foundation blocks and footings of buildings constructed within the last 3 to 20 years. Shortly thereafter, the first cases of AAR in foundation blocks in Fortaleza/CE were also discovered, as previously mentioned. (Otoch, 2016).
According to Battagin (2016), through IBRACON's dissemination work and the standardization of the number of tests performed at the ABCP laboratories, in the absence of statistics from other laboratories, it was found that the number of tests sent to ABCP has increased considerably throughout the country, in many construction-related areas. Aggregate samples have been sent by a diverse group, including aggregate suppliers (quarries), concrete service companies, construction companies, designers, universities, and even other laboratories, showing that the entire construction supply chain has gradually become aware of the importance of preventing pathological manifestations related to AAR. The profile of clients requesting tests and their geographic origin was determined, based on 1621 fine and coarse aggregate samples received by the ABCP laboratories, which had sufficient information, as shown in Figure 1. Most requests come from São Paulo (532 samples) and Pernambuco (228 samples), with requests being recorded from all Brazilian states except for Acre. (Battagin, 2016).
Considering this scenario found in Recife and neighboring cities in Pernambuco, a region with a high rate of occurrence of AAR, verified by the large increase in tests seeking to elucidate the

conditions of the aggregate, this paper presents the result of a documentary investigation performed at the main structural recovery companies of the RMR. The objective of the study was to trace a historical profile of the buildings' constructive characteristics, how the diagnosis was made, the procedures used in the intervention, the materials applied during the recovery, the use of jacketing with reinforcement, and the costs, as well as how the foundations that would be monitored after the recovery through an inspection window were identified. The interview provided data on fifty foundations affected by AAR, but this number is likely higher, providing ample possibilities for larger future studies.

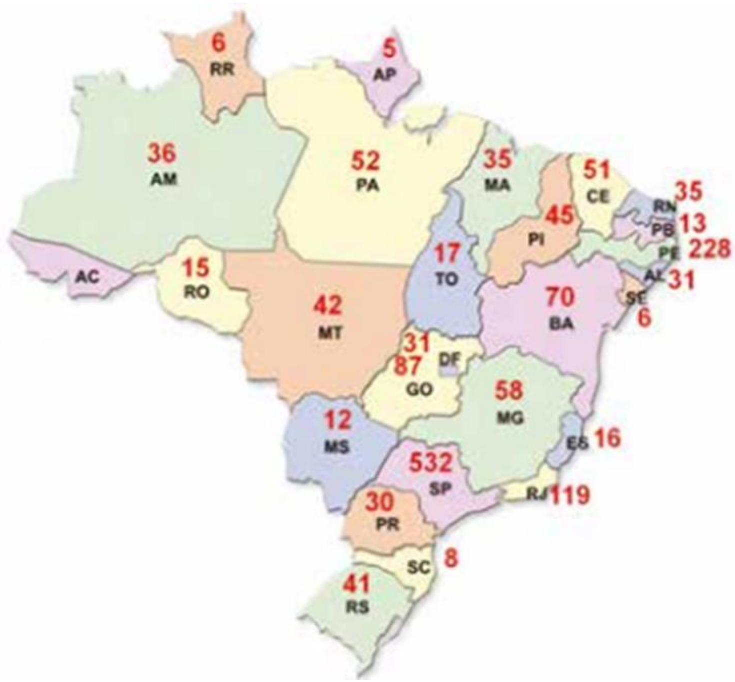

Figure 1. Distribution of samples by state (Battagin, 2016).

1.1 Description of the reaction and its types

The alkali-aggregate reaction is a chemical reaction that occurs in the internal structure of concrete and involves the alkaline hydroxides that appear because of cement hydration, and reactive minerals present in the aggregate. As a result of the reaction, products are generated that can expand in the presence of moisture, generating cracks, displacement, and the possible compromise of concrete structures. There are two types of alkali-aggregate reaction, classified according to the aggregate's reactive mineralogical composition, each with specific expansion mechanisms. The reactions are known as the alkali-silica reaction (ASR), the alkali-silicate reaction (ASSR), and the alkali-carbonate reaction (ACR).

1.1.1 Alkali-Silica Reaction (ASR)

According to Hasparyk (2005), the alkali-silica reaction is the most well-known type of AAR reported in the technical environment, as it is the one that usually occurs most rapidly, due to the reactive silica minerals involved. Among the most common minerals are opal or amorphous silica, chalcedony, cristobalite, tridymite, natural and artificial glass, microcrystalline/ cryptocrystalline quartz, and deformed quartz.

1.1.2 Alkali-Silicate Reaction (ASSR)

A specific type of alkali-silica reaction, called the alkali-silicate reaction, takes place between alkalis and reactive silicates present in sedimentary, metamorphic, and igneous rocks. It presents the same mechanism as the alkali-silica reaction but occurs more slowly. (Andrade, Silva, 2006).

1.1.3 Alkali Carbonate Reaction (ACR)

This reaction occurs more rarely and without gel formation. It is characterized by the expansion of carbonate rocks, because of the reaction with alkalis, mainly from the cement paste and dolomitic limestone, generating crystallized compounds such as brucite, alkaline carbonates, calcium carbonate, and magnesium silicate. This expansion, called dedolomitization, is the cause of cracks that appear in concrete because of the weakening of the paste-aggregate bond. In this reaction, alkalis are formed again, allowing the dedolomitization to continue until the dolomite has reacted completely or until the alkali concentration is sufficiently reduced. (Andrade, Silva, 2006).

1.2 Behavior of affected structures

The symptoms of a structure with AAR present themselves through the appearance of a gel exudation on the concrete surface, edges around aggregates, pores filled with white or glassy material, cracking, and discoloration of the concrete. Cracks having a map configuration occur more frequently in road pavements, airport runways, walls, and faces of structural elements, which have low restriction to expansion in the three directions. According to Hasparyk (2005), the main deleterious effects caused by AAR in a structure are the following: cracking on the concrete surface and between concrete layers; debonding of the concrete surface; loss of watertightness; displacement (loss of adhesion) of mortar near the surface of aggregates; movement (opening or relative displacement) of contraction joints; opening of construction joints, with horizontal cracks; movement/misalignment of free surfaces (such as raising of a dam’s crest and spillway sills or deflections in dam structures) and locking or displacement of equipment and moving parts (gates, turbines, shafts, and pistons, among others).

2. METHODOLOGY

2.1 Initial considerations

The study designed for this paper was a documentary investigation, developed in the cities of Recife and Jaboatão dos Guararapes, cities where the largest number of foundations affected by the alkali-aggregate reaction were found. In Brazil all reported cases of the reaction to date are exclusively of the alkali-silica type (ASR), as will be shown below. This study compiles and analyzes the building characteristics, diagnoses, procedures, costs, results obtained from consulting company files, as well as interviews with engineers working in the field of rehabilitation, for fifty cases where foundations have been affected by this reaction.

It is worth pointing out that, while there were no problems or restrictions on the part of the companies involved in providing the information, only a small number of records regarding recovered foundations were found. This is likely because condominiums make their budgets with companies that have proven experience, and these, when issuing their reports with the materials necessary to remedy the damage caused by the deleterious reaction, are dismissed. As time goes by, it is verified that these recoveries were executed by those with "doubtful" skills, which may compromise the efficacy of the services rendered. When this occurs, these foundations are no longer properly analyzed, and consequently the results of these recoveries may end in failure, due to poorly executed processes.

Although the technical community has been aware of this reaction for more than 85 years, as well as its forms of prevention, the deterioration of concrete resulting from the reaction is still

considered relevant, especially because of its serious repercussions to foundations and the great inconvenience caused to infrastructure and building projects.
Based on this context and considering that Recife is among the cities having the highest number of AAR cases recorded in the Brazilian literature, an investigation was conducted to collect data on the topic, starting in December 2018 and concluding in July 2019. The methodology used was divided into four stages, as shown in Figure 2. This methodology was based on interviews at the largest possible number of companies that carried recoveries on foundations affected by the alkali-aggregate reaction, through the application of a 17-question survey, shown in Table 1.

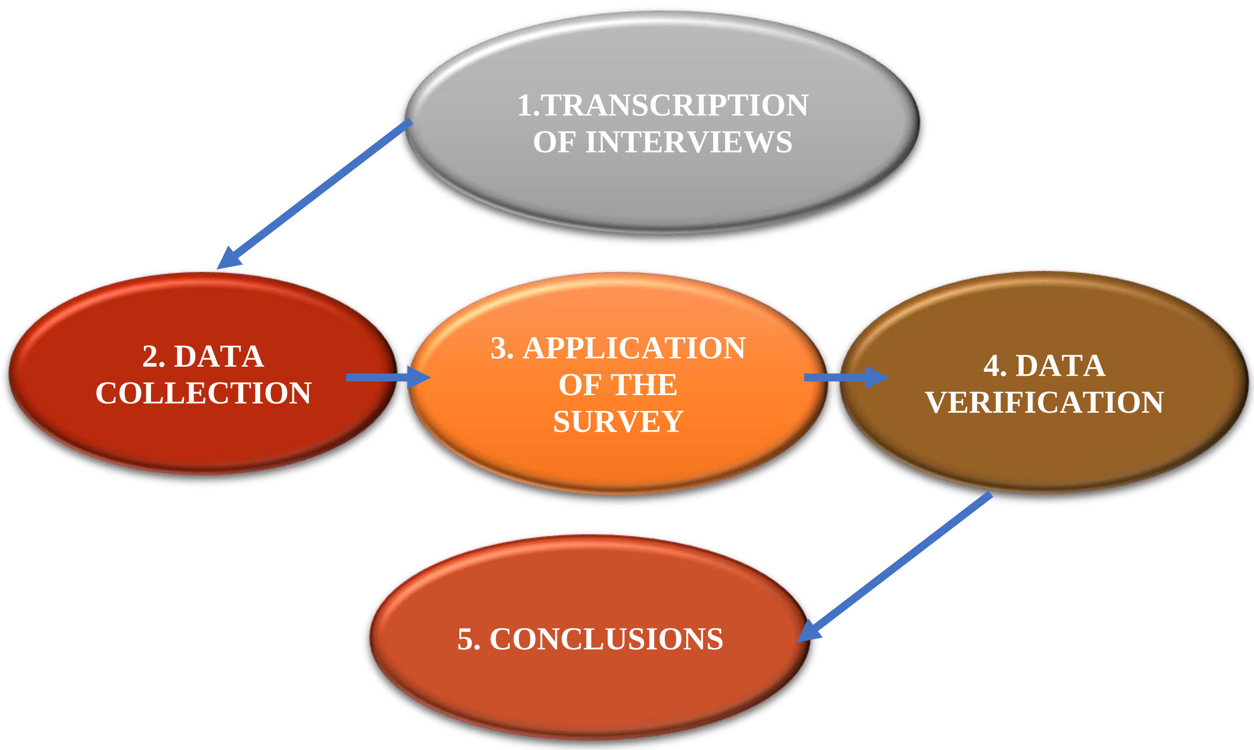

Figure 2. Methodology applied at the interviewed companies.

2.2 Transcription of Interviews
The first step was to conduct interviews at the companies in the construction chain, informing them about the purpose of the study and the need for updated data regarding any foundations that were recovered.

Table 1. Survey applied during the interviews.

Building:			
1.0	**Building Characteristics:**		
1.1	What is the building function?		
	Residential		Commercial
1.2	How many floors?		
1.3	What is the height of the water table?		
1.4	What is the building age?		
1.5	How was the problem discovered?. What were the symptoms?		
1.6	How far from the sea is the building?		
1.7	What is the type of the foundation?		
2.0	**How was the diagnosis made?**		
2.1	Location of cracks' incidence in the building:		
2.2	How was the pathology diagnosed?		
2.3	What test were performed to determine the pathology?		
3.0	**How were the recovery procedures made?**		
3.1	What steps have been taken?		
3.2	How was the filling of the cracks done?. What equipment was used in the recovery?		
3.3	Was the reinforcement project prepared by the structural engineer?		
3.4	Was it done any encapsulation?		
	Yes		No
3.5	Was waterproofing done?		
4.0	**Who was responsible for the costs of recovery?**		
4.1	Who was responsible for the payment?		
4.2	Was an inspection window left after recovery?		
5.0	**Comments:**		

2.3 Data Collection

For this study, information was gathered on fifty buildings, both commercial and residential, for which their foundations had undergone a recovery procedure.

In the city of Recife, the recoveries had been performed on buildings located in the districts of Graças, Casa Forte, Espinheiro, Derby, Boa Vista, Madalena, Boa Viagem, and Setúbal, with an emphasis on the district of Boa Viagem.

In the city of Jaboatão dos Guararapes, the recoveries were performed in a building located in Piedade.

The companies that participated in this universe of information were very receptive and provided all the necessary elements, with the understanding that the identities of the buildings listed and of the companies themselves would remain confidential. Thus, each company was referred to by a random letter, not associated with its name. Table 2 provides a general survey of the companies consulted, showing their activities and the total number of foundations detected.

The first company interviewed was A Engineering.

Founded in 1995, Company A operates in the field of civil construction, specializing in recovery and strengthening structures made of reinforced and prestressed concrete. With a collection of more than 600 concluded projects during 24 years in the market, its portfolio includes excellence in building structures in marine environments, treating apparent concrete, recovering and reinforcing water mains, and structural reinforcement, among others.

In this company, thirty buildings were cataloged in the period from December 2018 to May 2019 in which AAR was identified.

The second company was X Engineering.

Founded in 1981, its construction portfolio contains a wide range of modern buildings, including port structures, real estate developments, special works of art, recovery and structural reinforcement in buildings and works of art, and conservation and restoration of buildings of historical heritage.

Three buildings from this company were catalogued with identified AAR, including a restoration project on a commercial building. However, the other recoveries executed by the company in question are outside the scope of this work, which, despite dealing with the recovery of foundations with ASR, are neither residential nor commercial buildings.

The third company was Y Engineering.

It was founded in April 2000, with the objective of providing specialized technical services to the civil construction sector, including restoration and reinforcement of reinforced concrete structural elements, which is its principal activity. The specialized services of restoration and structural reinforcement make delicate to disclose by name the projects that make up its technical portfolio, which consists of approximately 350 executed projects. In this company, seven buildings that went through the restoration process were catalogued.

The fourth company was Z Engineering.

With more than 12 years of experience, this company provides technical civil engineering services in the areas of building restoration and maintenance. Three buildings where AAR was identified were catalogued from this company.

The fifth company was T Engineering.

Founded in January 2003 in the city of Recife, it is now active nationally with a portfolio that includes more than 500 customers. It offers services in the areas of expert technical assistance, consultancy, project management and inspection, expert reports, monitoring, and technical follow-up, among others. Seven buildings from this company with AAR were catalogued.

Table 2. Companies participating in the interviews.

Company	Operation	Experience	Time Experience	Number of cases
A	Structural reinforcement	Marine structures, concrete treatments, recovery, and reinforcement	24 years	30
X	Structural reinforcement	Port structures, special works of art, recovery, and reinforcement and restorations	38 years	03
Y	Structural reinforcement	Recovery and reinforcement of foundations	19 years	07
Z	Structural reinforcement	Recovery and reinforcement of foundations and maintenance of buildings	12 years	03
T	Monitoring of reinforcement	Expert technical assistance, consultancies, report, and technical monitoring	16 years	07
TOTAL				**50**

2.4 Application of the questionnaire

The third step was the application of a questionnaire containing fifteen questions about commercial and residential buildings where the ASR pathology was proven and recovered. During application of the questionnaire, shown in Table 2, information was sought about the pathological manifestation, a history of the project's characteristics, how the diagnosis was determined, the recovery process, and its costs.

2.5 Data verification

After collecting the data, the fourth step began, that of analyzing all the material acquired during the study, searching for photos, reports, and test results to add to the researched material.
A spreadsheet was created based on the answers supplied to the questionnaires, with data on each construction project, including characteristics such as age, recovery type, materials used, test type, year of recovery, etc. This can be seen in Table 3. These data were added up and the percentages for each item analyzed were obtained. The graphs (Figures) were created from these results with their respective identifications.

Table 3. Spreadsheet with compositions.

SPREADSHEET WITH COMPOSITIONS																	
COMPANY X	REFERENCES	CHARACTERISTICS						DIAGNOSIS			REINFORCEMENT			COSTS		PECT	
		USE	NO. FLOORS	WATER TABLE	AGE	SYMPTOMS	FOUNDATION	LOCATION	PATHOLOGY	TESTS	PHASES	STRUCT. ENG.	AP. SULAT	CONDOMNIUM	CONST. COMPANY	Y	N

2.6 Discussion

Finally, all the collected materials were verified to analyze the characteristics of each project, the procedure applied in determining its pathological manifestation, the diagnosis, the recovery process, and the cost.
It was found that interventions in the foundations occurred because of the need to investigate and verify their condition. It is believed that these investigations occurred due to two main factors. The

first was the collapse of the Areia Branca building, which put many condominium owners in a state of alert to check their structures, and the second was the obligation imposed by Law Nº 13341. This law made periodic inspections mandatory, making it possible to identify a greater number of foundation recoveries and other pathologies previously neglected due to poor or infrequent maintenance habits.

3. RESULTS AND DISCUSSION

3.1 Data analysis

For the data analysis, the questionnaire was divided into four parts. The first part dealt with characteristics of the building, the second part with the diagnosis, the third part described how the restoration was performed, and the final part was on the restoration costs.

3.2 Building Characteristics

The first data collected were the building characteristics, consisting of seven questions, from which it was possible to get a relevant idea of any preponderant factors for the appearance of AAR. The questions followed this order: building use, number of floors, height of the water table, age of the building, how the problem was discovered and what symptoms were found, the distance from the sea to the building, and the foundation type.

3.2.1 Building Use

Of the 50 buildings verified, only 4% were commercial buildings, with the remaining 96% being residential buildings. Most of the buildings currently verified and recorded in this study are effectively residential buildings, as shown in Figure 3.

3.2.2 Number of Floors

The study analyzed buildings that varied in their number of floors. The floor count included common floors such as basements, the ground floor, open floors, typical floors, and any penthouse floor.

Figure 4 shows the percentage of buildings based on their floor count, divided into categories having 15 floors or fewer, 16 to 25 floors, and more than 25 floors (with the tallest building having 41 floors) for a total of 50 catalogued buildings.

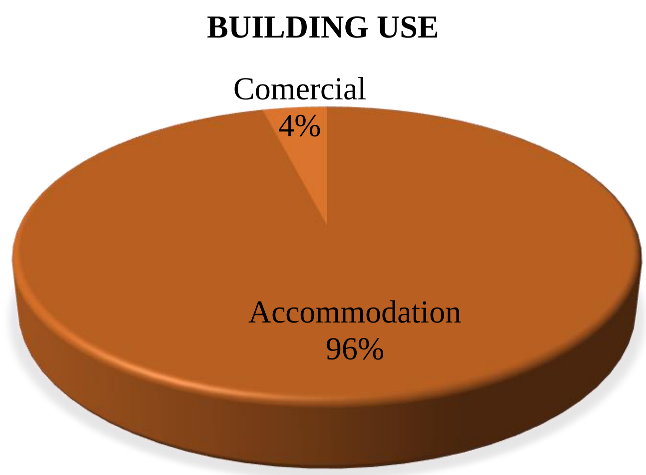

Figure 3. Building Function

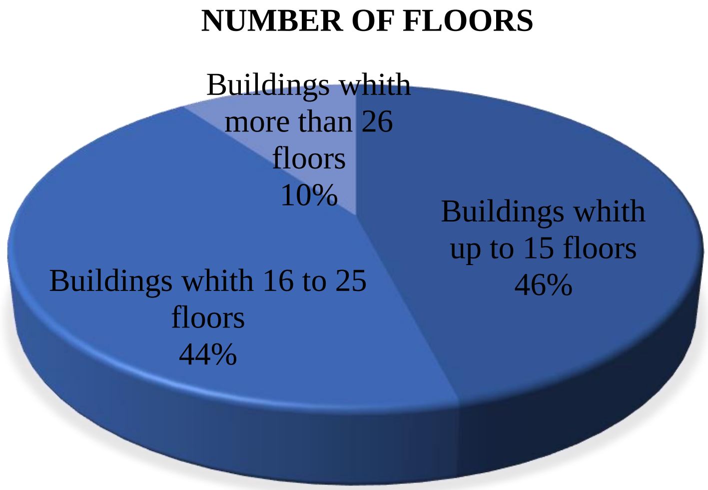

Figure 4. Number of Floors

3.2.3 Height of the Water Table

The occurrence of ASR is directly linked to three factors: alkali materials normally found in the cement, reactive aggregate, and the presence of water. In this study, attempts were made to determine whether any water was found during the recovery process that would favor the occurrence of the reaction.

When the foundation was excavated, any occurrence of water was identified, either from the water table or from any other source. In foundations where the water table could be identified, the elements were either partially below it or with water just reaching their lowest point. The AAR phenomenon develops not only in concrete elements that are below the water level, but also those where only the lowest part of the block was in contact with water.

At some companies, this information was made available during the interviews, while in other cases it was possible to identify from the collection of photos. In still other situations, the itemization of the budget showed costs for lowering the water table, i.e., the recovery work could only be performed after lowering the water table. In these cases, the original water level was unknown, and was therefore considered to be at the bottom of the block. In a few cases, there was no information at all regarding the presence of water, so the water table was not found.

Based on these assumptions, the level of the water table was grouped into four categories, defined by its level in relation to the elevation of the foundation element: Level 1, Level 2, Level 3, and NE, described below:

Level 1: water table at the bottom level of the block.

Level 2: water table in the middle of the block.

Level 3: water table at the top of the block.

NF: water table not found.

After all the analyses at the company level, Table 4 was created to summarize the water table results and address their relationship with the 50 foundations in a general way. Forty percent of the foundations had water at the bottom level of the block (level 1); 18% had water in the middle of the block (level 2); while no foundations were identified with water at the top of the block (level 3). Water table information was not found for 42% of the foundations surveyed.

Table 4. Water table levels found.

Summary of water table levels				
Companies	LEVEL 1 – Water at the bottom level of the clock	LEVEL 2 – Water in the middle of the block	LEVEL 1 – Water at the top of the block	NF – Level not found
Z Engineering	50%	25%	0	25%
X Engineering	67%	33%	0	0
A Engineering	17%	20%	0	63%
Y Engineering	100%	0	0	0
T Engineering	61%	17%	0	17%
Total	40%	18%	0	42%

3.2.4 Building Age

The study also attempted to identify the ages of each building, starting from year 1, when construction was finished, until the time it was catalogued by the company responsible for its recovery. However, this information was not made available for all the cases studied. The buildings were of different ages at the time of their recovery from ASR.

The youngest buildings found were thirteen years old at the time of recovery, with footing foundations. Other buildings had pile and footing foundations with ages of 16, 19, 20, 30, and up to 45 years. In Figure 5, the information was categorized into ranges of up to 20 years, from 21 to 30 years, from 31 to 40 years, and finally 41 years and up.

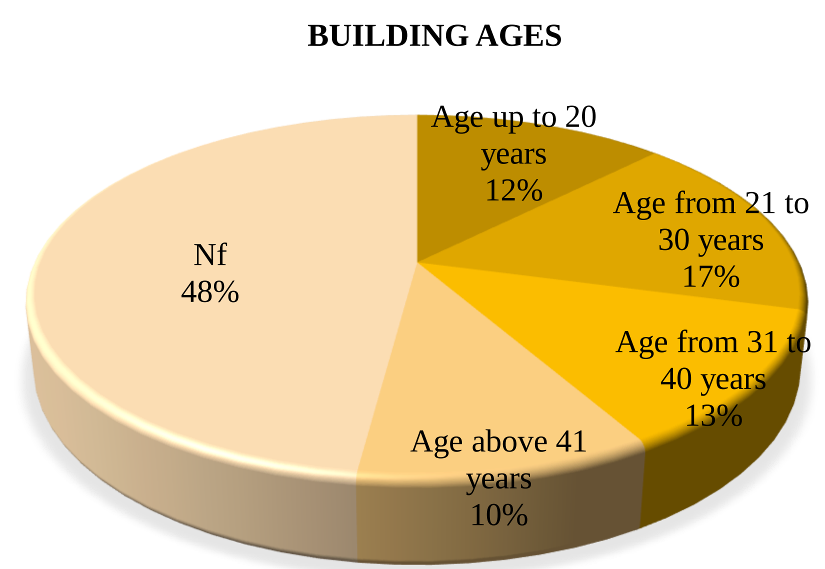

Figure 5. Building age ranges.

These AAR-affected foundations were discovered because of the situations previously mentioned, the collapse of the Areia Branca building and, consequently, Law 13.032, which required condominiums to perform inspections. From then on, the discoveries were determinant, with

verification of the reaction through tests, such as the Petrographic test, to identify the degree of aggressiveness of the reaction in the foundation elements, a parameter that would indicate the necessity of any urgent intervention.
The years in which the recoveries took place also varied, but the occurred mainly in 2005, 2008, 2009, 2011, 2012, and extend until today.

3.2.5 Discovery of the pathology and the symptoms found.

There are usually difficulties associated with interpreting the occurrence of cracks or structural damage, has been recurrent lately. These problems may be caused by various factors such as failures during the design phase of the project, use of incorrect materials, poor construction procedures, or lack of proper maintenance.
Symptoms are the characteristic external manifestations of pathological problems, from which the nature, origin, and mechanisms of the phenomena involved can be deduced, as well as their probable consequences. These symptoms, also called lesions, damage, defects, or pathological manifestations, can be described and classified from detailed and experienced visual observations, guiding an initial diagnosis of the problem (Helene, 1992).
In this study, the symptoms found are easily confused with the discovery of the pathology, because in 80% of the cases identified, the causes cited were cracks. These usually propagate across the floor, and in some cases were found on the pillars of the basement, ground floor, or open floor, and are identified by their effect on the floor immediately above the blocks or footings.

3.2.6 Distance of the building from the sea

The proximity to marine areas was analyzed because, according to NBR 6118: (2014), these areas are considered to have a degree of aggressiveness of III, considered strong.
It was found that most of the recovered foundations, 54%, are in the southern zone, in the Boa Viagem neighborhood near the sea. The remaining foundations are in the northern zone, in more distant areas. Normally, in the south zone, the water table is high, which could have provided a favorable environment for the reaction to begin in the foundations.

3.2.7 Foundation Type

Cracks were one of the most common symptoms found in foundations. There are numerous difficulties in interpreting the pathologies caused by the alkali-silica reaction (ASR), however it is correct to state that a structure affected by this reaction will show the presence of the exuded gel that results from the reaction. In the early stages, or under conditions where only small amounts were formed, ASR cannot be visualized with the naked eye, requiring specialists and tests performed on samples taken from the affected material, to detect it.
According to Silva (2013), renowned engineers active in the construction market indicated that some changes have been done to foundation designs to mitigate the deleterious effects of the reaction. There was a change in the reinforcement detailing of the foundation elements, especially in the pile caps, which, because of their high concrete volumes, have thicker reinforcement on the sides and top (through meshes forming a cage), to avoid or minimize possible cracking due to concrete expansion.
In the case of this study, where the buildings in question were older than 15 years, the projects had not undergone any changes as a response to the reaction. Figure 6 shows that, of the fifty buildings mentioned, only two had footings as a foundation element (4%), while the other 96% had block foundations.

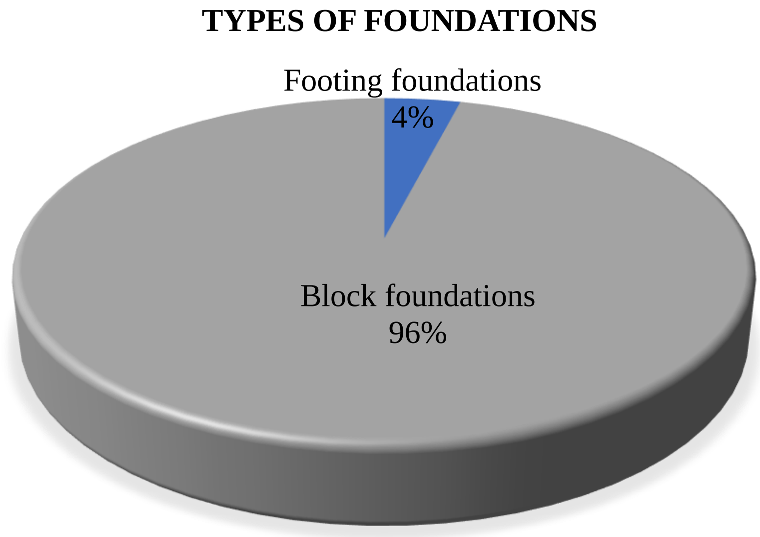

Figure 6. Foundation Types.

3.3 Diagnosis

The diagnosis of concrete structures affected by the alkali-aggregate reaction is carried out in steps: information collection, visual inspection, concrete component material sample and extracted core tests, sonic auscultation, and follow-up of its evolution through mathematical modeling (Priszkulnik, 2005).

The diagnosis of the affected foundations was performed using visual information and the results of the tests performed on the concrete cores, concluding the existence of the alkali-silica reaction. Detailed situations were reported about the state of the foundations affected by the reaction, such as the formation of cracks. The core extraction was an important tool that allowed for the identification of internal cracks, loss of mortar adherence at the interface with the aggregates, reaction edges around the aggregates that have reacted with alkali, gel within the voids, and the carbonation depth.

3.3.1 Location of cracks in the building

The locations where cracks were found were very similar among the buildings. The cracks were found mostly through routine inspections or because of their effects on the floors. The foundation elements were cracked on the top and on the sides. A preliminary mapping of the structural elements was carried out, where the positioning of the cracks, their direction, their thickness, and where they were most concentrated was verified.

Only after joining all the information from the visual inspections, the tests, and the building's design and construction documentation, was it possible to analyze and diagnose the problem. It is important to emphasize the need for laboratory tests to confirm the presence of the alkali-silica reaction.

The companies involved the recovery work also reported that visual inspections, as well as project verifications, are done, but only 48% of the companies used laboratory tests. The other 52% only took into consideration visual information, as shown in Figure 7. In some circumstances, due to financial issues, the tests are dispensed with. In other cases, after checking *in loco* the state of the foundation, the deleterious reaction was so advanced, as shown in Figure 8, that recovery became critical, causing condominium owners to accept the diagnosis solely based on the companies' experience.

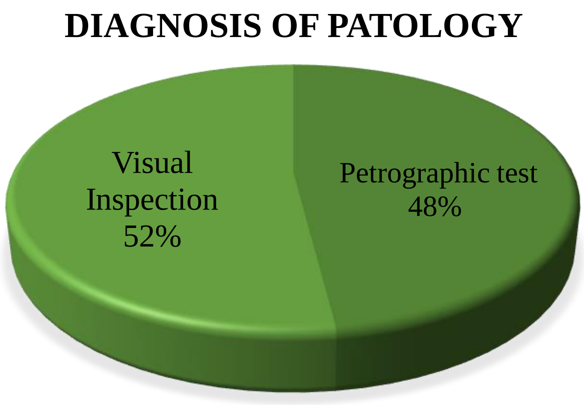

Figure 7. Diagnosis of the pathology.

Figure 8. Cracks on a block with AAR.

There are currently several standardized methods on the market to characterize the potential expansive reactivity of mineral aggregates in Portland cement concrete. Petrographic analysis is used to diagnosis the presence of reactive material and also to find any occurrences of manifestations associated with the reaction, such as a reaction edge around the aggregate, microcracks caused by expansion, or presence of gel within the pores, among others.

The test used to determine the pathologies in this research was the NBR 15577-3: (2013) Petrographic test. Unfortunately, as presented above, due to costs, the tests were not performed. In the cases investigated, the cores extracted from the foundation elements were sent to the Brazilian Association of Technical Standards (ABCP) or to the Institute for Technological Research (IPT), both in São Paulo. Most of the petrographic tests (80%) were performed by ABCP and the rest by IPT.

3.4 Recovery Procedures

With recovery processes for concrete structures, the quality of the result depends primarily on an accurate diagnosis and an appropriate choice of recovery method, which includes the selection of materials and equipment necessary to carry out the service.

This was evidenced when examining the requests for foundation recovery projects where the expansive reaction had reached a high level of deterioration. In addition to these issues, information on the properties of the concrete exposed to the reaction was sought, a condition imposed by the companies to verify the condition of the previous concretes to be able to guarantee good results from the intervention and recovery services.

With this data available, the recovery process and the steps to be followed can be determined, , the safety procedures applied, and the materials chosen that be used in the fight against ASR.

3.4.1 Steps followed in the recovery process.

The steps followed in the foundation recovery intervention process resemble a prescription for treating a disease. This process was followed and carried out by all five companies interviewed in this study for most of the recoveries, with only the materials used being changed for monolithization.

The formulation of these recovery treatments was adjusted regarding size, direction, and depth of the cracks. When it comes to the ASR recovery process, the aim is to guarantee that the structural pieces can return to working, monolithically, by closing of cracks through the injection of an adherent and resistant material. The steps that make up the recovery and their order of execution are described below:

Demolition and excavation of the materials; washing of the concrete surfaces; chipping of the surfaces; drilling of the concrete; filling and placement of the ports; injection into the cracks; and mounting of the reinforcement and structural concrete.

3.4.2 Crack filling and materials used.

Injection is the last step in the recovery process and its purpose is to perfectly fill the space formed between the edges of a crack, recomposing the foundation, and promoting its monolithism. The procedures executed during crack filling had some slight variations from one company to another, depending on the state in which the structural element was found, and the criteria developed for the injection.

In the various treatments studied it was necessary to use materials that had a high mechanical resistance to compression, traction, and shear, and epoxy resin was one of the materials recommended for the treatment of cracks and fissures affected by ASR. Because it is a rigid material after curing, it is important to restrict its use to passive fissures and cracks, i.e., those that present no movement, as was the case with the foundations cited in this study.

The second material used for the injections was microcement. Relatively new for this procedure, it is a material created from cement itself having a grain fineness of less than 8 micrometers, or 8 thousandths of a millimeter, with 95% of the particles having the same size. It is a rigid material after curing and can be used for passive crack filling in wet or dry areas. Some companies have opted for this material because it provides structure along with alkaline protection for the reinforcement, resistance to compression, traction, and shear, and fills voids, bringing back the structure's monolithism and resistance.

In the research it was found a greater use of epoxy resins in 82% of the foundations, followed by microcement in 6% of the foundations, and in 10% the material used was not identified, as shown in figure 9.

This study found that epoxy resins were used in 82% of the foundations, with microcement used in only 6% of the foundations. For the remaining 10%, the material used was not identified, as shown in figure 9.

In the injection process, plastic and metallic ports were used, as shown in Figures 10 and 11. The metallic ports are part of the new advances in the injection process, to which an injection can be applied under higher pressure, and consequently the penetration of the material to areas of greater depths can occur in a shorter span of time. However, from the data collected in this study, filling was done to close external cracks and ensure the injection, and the most used materials were plastic ports, which are simpler and easier to find on the market.

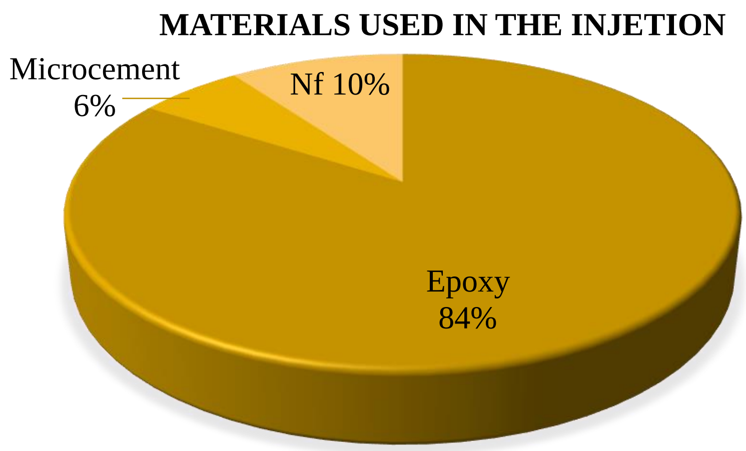

Figure 9. Materials used for injection.

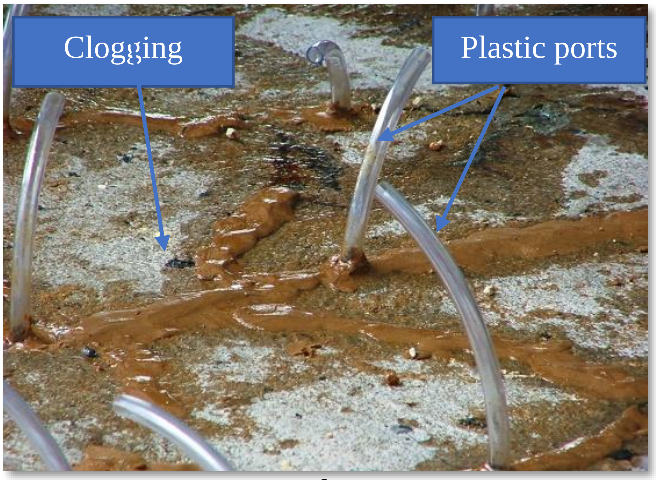

Figure 10. Plastic ports.

Figure 11. Metallic ports.

3.4.3 Jacketing and calculation of reinforcement

According to Silva (2007), to encapsulate the blocks affected by the expansive phenomenon of ASR, it is important to first have an understanding about the behavior of the structure to be recovered. With the appearance of the alkali-silica reaction in the foundation blocks of buildings in the Recife Metropolitan Region, understanding the behavior of these structures has become a challenge for technicians and structural engineers. It is important to establish an accurate diagnosis and adopt techniques that effectively resolve the problem, that is, those that give the building back its stability and reliability.

Regarding the affected foundations, areas with little reinforcement were susceptible to expansion caused by the reaction. Laboratory tests have shown that, in concrete, the expansion is restricted to areas where no strong compressions occur. In other words, foundations such as footings, which at the time had little or reinforcement, and that only on the lower and upper areas, were susceptible to expansion. Calculation of the reinforcement was determined in some cases through the intervention of engineers. The evaluation for use in the recovery project was determined as a function of the expansion found. In foundations with advanced deleterious reaction, verification by an engineer was requested. Reinforcement jacketing was used in 81% of the foundation elements with 19% not being identified, as shown in Figure 12.

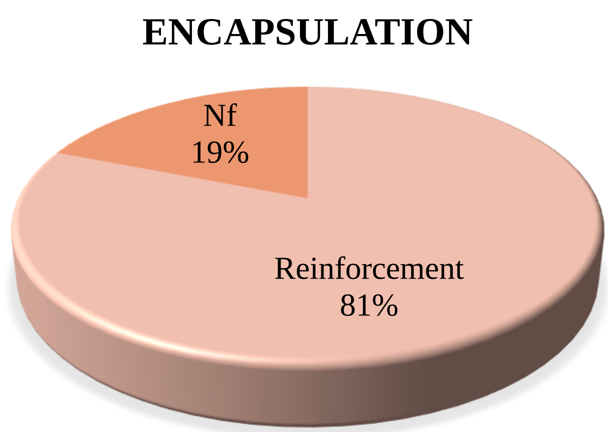

Figura 12. Use of reinforcement.

3.4.4 Waterproofing

During construction of the foundations, either footings or blocks, the health and durability of the foundation was ensured through waterproofing. This is an important step due to these elements being in permanent contact with soil moisture, which, when not treated, will conduct water into the block through capillarity.

To avoid possible pathological problems caused by moisture, it is imperative to use a waterproofing system that is compatible with the geometry of the pieces and the characteristics of the structure, such as the level of the water table. It was verified in this study that all the recovered foundations used waterproofing on the tops and sides of the elements, as shown in Figure 13.

Figure 13. Waterproofed block.

3.5 Recovery costs

The resources spent on the recovery depended on the type of intervention requested and the values presented. The cost of the recovery was directly proportional to the solution adopted for execution, considering methodology, material specifications, labor used, as well as complementary work, such as shoring and scaffolding, sump pumps, and others.

The study verified that the costs, which are quite onerous, are the condominium's responsibility and were varied and divided into two groups, according to the ability of each condominium to pay. The first group performed a complete recovery in 100% of the foundations, while the second group performed recovery in parts and over long periods.

3.6 Inspection window

As a result, it was found that, of the 50 foundations surveyed, only two left the inspection windows. The windows are small openings left in the foundation elements that make it possible to monitor the recoveries from the floors above, as shown in Figure 14. Internally, small pieces of glass are placed, shown in Figure 15, where cracks had previously been identified, so that they can be periodically monitored after their recovery. If any new movement of the foundation block occurs, the tendency will be for this glass to break, indicating a possible continuing of the ASR, or of some other pathological manifestation.

Figure 14. Inspection window.

Figure 15. Interior of inspection window.

4. FINAL CONSIDERATIONS

This study aimed to create a profile of the processes used in the recovery of foundations affected by the alkali-silica reaction, by analyzing case studies of 50 recovered foundations. The results are presented in four parts: characteristics, diagnosis, recovery, and costs. The analyses of the initial results provided the following statements about the construction characteristics:

- With regard to building use, 96% are residential and 4% are commercial.
- Structures with 15, 25, 30, and up to 41 floors were found.
- Regarding conditioning factors that influence the reaction, it was established that several foundations had their elements partially submerged below the water table. It was found that 40% of the foundations were at level 1, i.e., the water table was in permanent contact with the lower part of the block; for 18% of the foundations, water reached the middle of the block, level 2; while no blocks were found at level 3. In 42% of the foundations the water table was not identified.
- The ages of the buildings ranged from 10, 15, 16, 20, 22, 25, 30, 40, 41, up to 45 years old.
- Discovery of the pathologies occurred through routine checks that found the appearance of cracks on the parking lot floors in 80% of the cases studied.
- Regarding distance from the sea, 54% of the buildings were located in the south zone of the city (near the sea), while 46% were in the north zone.
- Only 4% of the foundations were of the footing type, with the other 96% made of blocks.

Regarding diagnosis, the following information was found:

- The location of the cracks was identified as being on the sides and tops of the blocks and footings.
- Only 42% of diagnoses made use of laboratory tests. Through studies that included the participation of engineers and concrete specialists, and considering the evident cracks, the age of the building, and the environment where the foundation was located, an ASR recovery ASR methodology was developed based on test results from core extractions that supported a procedure to combat expansion. However, in 58% of the cases, the opinions of business owners were sought, some of whom had considerable experience working with recovery processes and others who had experience with other aspects of construction, who, without the presence of engineers nor laboratory test results, determined that the intervention should be treated as alkali-silica reaction, and followed a recovery procedure used in other cases.

- The Petrographic test was used to diagnose the reaction in 42% of the foundations, while the remaining 58% were diagnosed through visual tests only.

The following information was observed about the recoveries:

- The recoveries were similar in most of the fifty verified foundations and followed this procedure: demolition and excavation of the structural elements, washing of the surface of the elements, chipping and drilling of the concrete, filling of holes, injection, assembly of the reinforcement, concreting, and waterproofing.
- The materials used to fill the cracks were epoxy in 84% of the foundations, microcement in 6% of the foundation, and were not identified for 10% of the foundations. Filling was done with the aid of a pneumatic injection pump.
- Jacketing was used in 81% of the foundations and was not identified for the other 19%. The choice of this process was based on the degree of deterioration of the foundation. In most degraded foundations, recoveries were performed through the intervention of an engineer's design.

The following information was compiled regarding costs and the use of a recovery window:

- The costs were paid in full by the condominiums, except for two recoveries. One split the costs fifty-fifty between the condominium and the construction company, while the other was the recovery of only four footings and was paid for by the builder. The cost of the recovery varied according to the dimensions of the elements, the degree of degradation of the foundation, and also the procedure chosen for restoration.
- The final objective was to verify whether an inspection window was left to facilitate future maintenance. In only 4% of the foundations was an inspection window placed.

5. CONCLUSIONS

The results of this study help to form a true panorama of the procedures used in recoveries from 2004 to the present day. The treatments applied had great similarities with only a few minor changes. In an interview with some of those responsible at the companies, it was found that, since the recovery carried out on the Paulo Guerra bridge in 2000, the materials and recovery procedures used have had few advances. For example, injection using plastic and metal ports, even although the system using plastic ports is still the most requested. Another verified change occurred in the materials used for injection, with the use of microcement. Epoxy remains, however, the most used material.

After the recovery of the foundations, an effective and systematic follow-up is necessary, because the alkali-silica reaction can reappear due to potential faults in the results of the interventions. This highlights the importance of installing inspection window that helps enable the follow-up checks, especially regarding the recovered foundations that were not monitored by qualified personnel nor used laboratory tests, important items for a coherent and proper determination of the procedures to follow. As a result, a complete diagnosis is lacking, which could lead to the use of improper recovery procedures that fail to correct the pathology. The attempts to keep costs as low as possible is often detrimental to best practices and the guarantee of good results. Of the fifty foundations surveyed, only two left inspection windows, meaning that a mere 4% of the surveyed projects made it possible to conduct a proper follow-up.

Information regarding the reaction chemistry, the aggregate microstructure, mitigating measures, and preventions, were verified in the researched materials, however it is necessary to look more closely at recovered foundations that did not respond efficiently to these procedures, nor retained their durability. The effectiveness of future results in combating AAR in older foundations should also be a reason for systematic follow-ups to guarantee their structural health.

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