COMBINED ATTACK FROM AAR AND DEF IN THE FOUNDATION BLOCKS OF A BUILDING

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Abstract

Quality and durability of concrete structures can be considerably affected by chemical attacks. This situation can lead structures to risks of performance and safety. Inspections and routine tests can not always infer the reality of the structure and sometimes supplementary laboratory tests are necessary to assist a correct diagnosis of the pathologies. Field inspections and compressive strength tests several times are neither enough nor conclusive. Furthermore, causes of deterioration are commonly attributed to just one factor, i.e., an alkali-aggregate reaction (AAR), a sulfate attack, or a corrosion incidence. The fact is that results of more detailed investigations have shown the potential deterioration of concrete structures by an association of AAR and DEF (Delayed Ettringite Formation).

This paper will describe a real case of associated attack (AAR+DEF), presenting some lab supplementary tests and analyses that had led to a correct diagnosis of those pathologies in the foundation blocks of a residential building, in Brazil. Repair and rehabilitation through crack grouting and use of reinforced and prestressed concrete were performed and will also be presented.

Keywords: Pathology, deterioration, concrete, AAR, DEF, repair.

1 INTRODUCTION

Concrete deterioration may occur as from the interaction between a structure and the environment in which it is inserted. Factors associated to the characteristics of the materials constituting concrete, but also related to the conditions of casting, curing, exposition and the conditions of concrete use may cause severe deterioration deriving from different types of attacks. The evolution of the consequences generated influence the performance and the durability of the structure in field and, consequently, its service life.

A number of types of attacks are likely to occur; they may be divided into chemical, physical, mechanical, electrochemical or biological processes. In practice, however, the phenomena are usually overlapped and, in this case, their interactions have to be taken into account. Both external factors and internal characteristics of the concrete may account for the attacks. Among the chemical attacks in concrete deterioration, the alkali-aggregate reaction and the attack by sulfates stand out.

When there is any suspected problem with the structure, the ideal is to start an investigation by means of field inspections; yet is often necessary to conduct a more thorough investigation by collecting samples in field for laboratory studies, besides surveying data on the materials, on the structure and on the surrounding environment so as to aid the correct diagnosis of the problem. It is known that several field inspections and strength tests alone may provide inconclusive data, seeing that visual manifestations are similar in some types of attack, and the strength may even increase, depending on the phenomenon installed, leading to mistaken conclusions regarding structure quality.

The cause for structure deterioration is usually attributed to a single factor, for example, the alkali-aggregate reaction (AAR), or to an attack by sulfates or even to corrosion. The fact is that results from more accurate investigations have currently shown the deterioration potential of concrete structures deriving from combined attacks, such as AAR and DEF (delayed ettringite formation), for example. The DEF symptoms are generally similar to those of AAR and of sulfate attack, with the presence of cracks, which may be mapped and filled. This attack occurs in hardened concrete at its

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first ages, when the concrete is exposed to high temperatures, be it by thermal cure or deriving from the excessive hydration heat generated during the first cement hydration reactions [1].

Ettringite is known not to be stable over 70°C, in some reported cases even at 65°C; it may decompose and form monosulfates; later, the sulfate ions are dissolved, favoring the formation of new ettringite, deteriorating the concrete by DEF. High pH is also known to favor the presence of monosulfate more than that of ettringite, besides the high concentration of sulfates both in the pore solution and by adsorption into the C-S-H structure [2]. However, when the pH falls, be it for the occurrence of AAR, from consumption of alkalis, or by leaching, ettringite formation favorably occurs, providing conditions for the joint installation of AAR and DEF. [2, 3, 4, 5]

Some practical cases reported in the technical environment of structures deteriorated by DEF may be consulted in [6,7].

Among some of the cases of combined deterioration (AAR/DEF) reported in the literature, the study conducted by Shayan and Morris [8] may be cited. The work shows a case study of a bridge in Australia presenting signs that the cement hydration heat has reached 80°C, causing DEF. The suspected AAR derived from visual investigations was confirmed by laboratory analyses showing that the aggregate of gneiss origin presented reactive quartz. The microscopic analyses indicated both characteristic products of AAR and sulfate phases associated to ettringite. Researchers believe that the intense cracking observed may have had AAR as the main cause, despite DEF having been detected in the concretes. Another study in 2008 [9] shows the deterioration of a bridge deck due to intense AAR and some installed DEF, with negative reflections on the modulus, and still indicating great residual expansion potential, despite the strength showing to be adequate.

Durand et *al.*[10] report on combined attacks, such as sulfate attacks, AAR, and frosting and defrosting in hydraulic structures in Quebec. Hypotheses such as DEF and the presence of sulfides in aggregates do not seem to apply seeing that the concretes did not reach sufficiently high temperatures for that, and the mineralogical/petrographic characteristics of the aggregates are not sufficiently particularized. The laboratory studies show high alkali content, capable of causing AAR, besides the presence of soluble sulfates, which account for forming secondary sulfate compounds.

Another case study [11] considered DEF the major source of cracking and deterioration is railway sleepers, for the lack of cure temperature control, besides the high consumption of cement employed in the concretes, although AAR was also detected and it interacted with the moist present in future expansions.

In laboratory, studies such as Owsiak [12] showed combined phenomena. Besides the tests having employed high cure temperatures (90°C), high alkali contents were used when reactive opal was used to replace sand. The results indicated AAR as the major cause, but with a contribution from DEF to the expansive phenomenon.

The Fagilde Dam, in Portugal, also undergoes cracking and displacements due to AAR and to internal sulfate attacks. The diagnostic studies were conducted in concrete cores extracted from the dam and analyzed in laboratory; the presence of gel and ettringite was confirmed, characterizing the different causes of deterioration [13].

The approach in this paper is the combined attack of AAR and DEF in concretes originating in the foundation blocks of a building in Brazil, showing some of the complementary laboratory investigations which led to the correct diagnosis of the installed pathologies.

2 MATERIALS AND METHODS

2.1 General

Having as a base the intense cracking in foundations blocks of a building in Brazil (Figure 1), aiming to diagnose the problem and to investigate its possible causes, investigations in field as from a thorough visual inspection, along with a program of laboratory studies were carried out in one block. It is worth stressing that the block in question has a compressive characteristic strength at 28 days of 35 MPa, is cage-like reinforced, that is, there is lower, upper and lateral reinforcement steel and its dimensions are: length 4.6 m, width 2.6 m and height 2 m. Cores about 40 cm in length were extracted from near the top surface of the concrete block for petrographic analysis.

They were initially defined in field and, after the visual inspection, in the places from which the concrete samples would be extracted. As from the concrete cores extracted, the samples were subjected to laboratory studies, as described as follows.

2.2 Methods for assessment and analysis

Trace reconstitution and sulfur analyses

The studies involving mix design reconstitution were conducted in two concrete specimens extracted. The chemical analyses were quantitative and basically performed using the gravimetric method; drying and calcination were also employed for analyzing the volatiles, after the fragmentation of the concretes and separation of the aggregate and mortar fractions from the concrete samples. The mix design reconstitutions were performed after the calculations on the non-volatile base, based on the "insoluble residue" as from the aggregates present and, in the "siliceous anhydride" and "calcium oxide", as from the cement [14, 15].

The specific chemical analyses for determining the sulfur were also gravimetric, of quantitative character, obtaining the total sulfur contents in the form of sulfates and of sulfides present in the aggregate and mortar samples. The contents determined represent the total values existing in the samples, after acid attack.

Petrographic/mineralogical analyses of aggregates

The petrographic/mineralogical investigations into the aggregates constituting the concretes were conducted by optical microscopy of transmitted and reflected light.

The optical microscopy analyses of transmitted light were performed on thin plates and allowed classifying the origin of the aggregates present, identifying the mineralogical constituents with semi-quantitative percentage, besides verifying the potentially reactive minerals from the alkali-aggregate reaction point of view, according to the Brazilian Standard NBR 15577/3[16], among other characteristics related to texture and petrogenetic relationships. It is worth stressing that the visual/macroscopic analysis preceded the optical microscopy analyses of the samples, before the preparation of the plates, observing the general characteristics of the material.

In the optical microscopy analysis, the use of reflected light permitted to identify the opaque minerals, and to more specifically investigate occasional sulfides present in these opaques in polished sections of the aggregate samples extracted from the concretes. In this case, two polished sections were prepared for each concrete. Their texture was observed, along with the alterations and interrelationships among these minerals present. Both qualitative and semi-quantitative analyses were performed at this stage.

Petrographic analyses of concretes

The concrete cores microstructure was assessed by a scanning electron microscope (SEM) with spectrometry by coupled X-ray dispersive energy (EDX), for studying the chemical elements present (in samples with fracture surfaces). In parallel, an X-ray diffractometer (mortar fraction of concretes) was used. The two studies aimed at assessing the microstructural alterations in the samples which could justify the important cracking occurrence observed in the blocks, consequently aiding the diagnosis of the installed phenomenon. Preceding these analyses, a thorough visual inspection was conducted and, in association, the optical microscope was used to aid in the petrographic analyses of concretes.

3 **RESULTS AND DISCUSSIONS**

3.1 Mix design reconstitution

The mix design reconstitution data obtained from the chemical analyses and from the proportioning of paste and aggregate fractions can be observed in Figure 2.

Having as a reference the mixes determined from the "insoluble residue", "siliceous anhydride" and "calcium oxide", no great variation was observed between the determinations for each sample and, on average, the mixes obtained were 1:3.1 and 1:3.2 for concretes 1 and 2, respectively, which were concretes of the same proportioning. By estimating the cement content in these concretes, from some generic parameters such as specific mass of the concrete constituents, chemical analysis of the reference cement and a probable w/c ratio of 0.5, values of 438 kg/m³ and 433 kg/m³ are reached for concretes 1 and 2, respectively.

These mix reconstitution studies were important to aid the diagnosis of the blocks problem even with the limitations presented by the technique. The estimated cement content represents, on average, 435 kg/m³ (considering a characteristic strength of 35 MPa). There is no data related to the adiabatic temperature rise of the concrete used in this specific construction. Thus, the estimated temperature for the present study was based on an internal data base of Desek Company. This contains several Brazilian civil works that have used the same cement type. Considering this data and a

probable temperature increase of 0.12°C for each kg/m³ of cement for the type of concrete under study, the adiabatic rise is of the order of 52°C. As this concrete was not precooled or postcooled, its casting temperature may have reached about 30°C, thus allowing an adiabatic temperature rise in the block to reach values close to 82°C.

As a consequence, the situation causes concern once temperatures over about 65°C may trigger delayed ettringite formation (DEF). Previous studies conducted by [17, 18, 19] showed this possibility. Tests have shown that for concrete containing Portland pozzolanic cement (Brazilian type CP IV) in the order of 350 kg/m³, the adiabatic rise in temperature was of approximately 35°C, rising to 45°C for a content of 450 kg/m³ of the same cement. In the studies reported in the literature, considering the fresh concrete temperature equal to 25°C (ambient temperature), which could be much higher depending on the casting region, the temperature peak is estimated to be approximately 60°C and 70°C, respectively. For a blended cement (Brazilian type CP II F containing up to 10% of grinded limestone), the peak in temperature would be 75°C for a 450 kg/m³ content, that is, a little higher than that for the Portland pozzolanic cement. Concretes containing CP IV were investigated by microstructural analyses, and the presence of DEF was confirmed. Considering the aforementioned, it is possible to state that the concretes studied and presented herein, with cement content of the order of 435 kg/m³, also showed to be susceptible to DEF.

3.2 Sulfur analyses

The sulfur analyses results, expressed in weight percentage, determined in the aggregate and mortar fractions of the concretes are depicted in the graph of Figure 3.

The study conducted by chemical analysis allows observing that the aggregates do not show to be a source of sulfur, be it by some sulfate or sulfide, indicating phases present solely in the mortar fraction of concretes, and in these, only as sulfates origin.

Calculating sulfur in terms of sulfurous anhydride (SO₃) and sulfates (SO₄) in the mortars, considering stoichiometric parameters commonly used, the data presented in Figure 4 are obtained. The SO₃ data reach values close to 1.0% and 1.4%; the SO₄ ones, approximately 1.2% and 1.7% for concretes 1 and 2, respectively.

Analyzing the average cement content of concretes (435 kg/m^3) obtained by mix reconstitution, estimating the mix employed in the concretes, and calculating the SO₃ content in relation to the cement mass, values close to 3% and 4.5% are obtained for concretes 1 and 2, respectively, showing a certain variation between the concretes. Anyway, the data obtained showed to be relatively high as regards cement-base composite, which indicates a favorable sulfate attack. According to the Brazilian cement specification standards, the maximum value admissible for sulfur trioxide in the cement is 4%. The concretes placed in the foundation blocks were known to have been made with cement without supplementary cementing materials such as those with pozzolanic characteristics.

In the ABNT Brazilian specification [20] for aggregates, an observation is also made concerning the limits in terms of SO_4 , as follows: "in case of total content brought to concrete by all of its components (water, aggregates, cement, additions and chemical admixtures) does not exceed 0.2% or if the use of sulfate-resistant Portland cement is proven, according to [21], the aggregate may be used. This standard also provides a limit of 0.1% for SO_4 in the aggregate (from soluble sulfates). Even though the concretes aggregates did not show any S contribution (Figure 3), if the total contribution of concrete is analyzed in the present study (mortar), the SO_4 values show to be far higher than the 0.2% limit (Figure 4) allowed, considering all the types of sulfate herein, and not only the soluble ones, but which may already be associated to deleterious phases.

3.3 Petrographic/mineralogical analyses of aggregates

The petrographic analyses performed in the aggregates from the concrete cores generally indicated mineralogical characteristics similar among themselves after the transmitted light optical microscopy analyses. The rocks employed as aggregates are generally of granitic origin.

The aggregates mainly consist of feldspars (microcline and plagioclase) and quartz, also containing micas (biotite and muscovite), but in a restricted way, besides some opaques and accessories in smaller proportion. It is important to stress that the mineralogical potentiality of the aggregates as regards alkali-aggregate reaction, taking as a reference [16, 22], show characteristics of reactive potentiality such as deformed quartz with undulatory extinction (varying from 15° to 35°). Potassium feldspars (microcline) were identified, which may also contribute to the expansive reaction. Figure 5 shows some of the major mineralogical characteristics of the aggregates constituting the concretes.

The analysis of the opaques present in the aggregates allowed identifying some of these minerals, such as ilmenite (iron oxide and titanium) and pirite (iron sulfide) in sample 01 and besides the minerals aforementioned, calcopirite (iron sulfide) was also found in sample 02. It is worth highlighting the considerably low incidence of these sulfides found by microscopy, besides their being well preserved, without any type of mineralogical alteration.

3.4 Petrographic analyses of concretes

The petrographic analyses of the concretes initially involving visual inspections, which precede the scanning electron microscope (SEM/EDS) analyses and followed the preparation of samples for SEM indicated characteristics not commonly found in normal concretes, be it on the surface of the concretes, be it within them, with their pores partially or totally filled with white material. Dark rims were also identified around some aggregates, suggesting alkali-aggregate reaction. Note that the two samples analyzed (Concrete 01 and 02) seemed similar in the visual inspection. Figures 6 (a, b and c) illustrates the major characteristics observed during the visual inspection of concretes.

Using optical microscopy, besides the important mineralogical characteristics observed in the aggregates during the petrographic analyses, characteristics indicating chemical reaction could also be verified in the plates prepared for the concretes, such as rims around the aggregates and pores containing deposition of material (Figures 7 and 8).

In the analyses involving scanning electron microscopy (SEM), the two concrete samples analyzed also showed to be very similar, and among the main characteristics observed are the pores (which in the visual inspection presented white depositions), independently of their size, containing acicular products mostly suggesting sulfate phases, besides massive formations. Some of the regions also showed some cracks following the pores, when filled with the neoformed products. Some other pores also contained silica alkaline cracked massive material characteristic of the gel, and among them some incidence of botryoidal formation as well as some crystallized rosette-like and lacy products, all of them characteristic of AAR [23]. The concentration of the two neoformed phases mentioned was also simultaneously observed at some points of the samples analyzed.

Acicular depositions on the aggregate were also visualized, suggesting reaction with the aggregate. The rims observed in the visual inspection indicate a reaction of the paste with the aggregate; this reaction can involve sulfate phases (from sulfides) or even alkali-aggregate reaction. In some localized regions, the aggregate was also fragmented; moreover, powdery material was verified, along with the punctual incidence of some cracks in the paste.

The micrographs in Figures 9 to 16 present some of the microstructural characteristics observed in the concretes analyzed, besides some of the spectra indicating the result of the microanalyses performed by EDS.

The analyses of the samples performed by X-ray diffraction aided those of SEM and allowed identifying the major mineralogical constituents of the concretes mortars. Let us stress, however, that the phases deriving from the aggregates often interfere and overlap those of the paste, hindering/masking the interpretations due to the high crystallinity of the minerals. The phases detected as deriving from the aggregates are compatible with the minerals present, and were the same for the two samples analyzed, corroborating the mineralogical microscopy analyses. In the phases indicated as deriving from the paste, ettringite and gypsite were found in sample 01, but only ettringite in sample 02. Hydroxides and calcium carbonates (portlandite and calcite) were also identified in both samples analyzed. By this X-ray diffraction technique, the presence of the sulfate phases visualized in the analyses performed by electronic microscopy are proven.

3.5 Repair and rehabilitation

The rehabilitation project aimed at recomposing all the 20 blocks monolithicity and strengthening it as well as trying to prevent the cracks from expanding, so as to preserve the compressed rods. Hence, the cracks at the top of the blocks with opening larger than 0.4 mm were filled with microcement and those with 0.2 mm \leq opening < 0.4 mm were injected with epoxy resin. Next, seeking free alignments between the pillars, Φ 32 mm Dywidag bars (ST 85/105 steel, meaning yield strength of 85 MPa and ultimate strength of 105 MPa) were placed in the upper and in the lower part, in two directions. The bars were anchored in "T" section steel braces, placed vertically on the lateral faces of the blocks. The bars prestressing occurred at stages, totaling 450 kN per bar and the final compressive stress applied to the block varied from 1 MPa to 1.2 MPa. The main problem faced by the design engineer was to find spaces where to place the prestressing bars, since there were several interferences and access conditions at the site. Another aspect that had to be solved was the placement of "T" section steel braces at the inferior part of the blocks. In the end, the whole system

was enveloped with concrete of characteristic strength equal to 30 MPa, water-cement ratio ≤ 0.45 , contemplating the addition of 10% of silica fume as well as waterproofing by applying a crystallizing agent by chemical penetration. Figure 17 to 20 depicts these steps.

4 CONCLUSIONS

Considering the cracking frame observed in field and having as a reference the results from the laboratory studies in the concrete cores presented herein, the concrete structure can be said to present chemical alterations, which may have affected its integrity.

The visual analyses had already indicated some of these alterations, from the different pores with depositions detected beyond the rims of some aggregates. In more detailed microstructural analyses, the neoformed products could be confirmed indicating phases both from the alkali-aggregate reaction and sulfate attack. The characteristic that stood out in this type of analysis was identifying the simultaneous presence of two types of pathology. Besides the verification of these facts, the chemical analyses also indicated the presence of sulfate phases in the concrete mortars, corroborating the microstructural analyses. A number of these products are already known and have been reported in the specialized literature [17, 24].

The incidence of alkali-aggregate reaction may be explained by the petrographic/mineralogical analyses of the aggregates constituting the concretes, in which potentially reactive minerals were detected. Concerning the sulfate sources, the hypothesis of their having originated in the aggregates, be it sulfates or sulfides, is discarded. In the specific mineralogical analysis of sulfides, these minerals did not show to be of importance for having caused some type of sulfate attacks, seeing its low incidence. In the chemical analyses of the aggregates, neither sulfates nor sulfides could be detected. Moreover, analyses of the region soil converge to low sulfate contents, which would thus eliminate the hypothesis of an external attack by sulfates. Therefore, and taking into consideration the mix design reconstitution data, as from the estimated cement consumption, and the possibility of the concrete mass having reached 80°C due to the hydration heat, in an association with AAR, the concretes very likely have undergone an internal attack by sulfates characteristic of the delayed ettringite formation (DEF).

As a result from AAR, products are known to be formed; if there is moist, they can expand, generating cracks, displacements and may even lead to damages in the concrete structures.

In turn, the reactions involving sulfates, denominated sulfate attacks, are also expansive chemical reactions in which sulfates react with the cement paste, originating mostly ettringite; gypsite may also form. Depending on the source, degree and type of sulfate attacks, this process may also lead concrete to deterioration due to the expansions, cracking, among other structural problems.

Based on the AAR and DEF diagnosis, the foundation block from which the concrete cores were extracted has its durability compromised considering that the mitigating measures for the types of attack involved are mostly palliative. A global analysis of the same block, as well as of the other blocks in the building in question, was performed, taking into consideration not only the type of structure, but also its exposition conditions, among other aspects and characteristics made important when the aim is to assess the influence of the pathologies installed on its performance and durability along with the need of occasional interventions in them. The rehabilitation project was directed towards recomposing the monolithicity of the blocks and to try and prevent the cracks from expanding by grouting them, besides prestressing and waterproofing the blocks.

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FIGURE 3: Sulfur contents from sulfate and sulfide in aggregates and mortars (expressed in weight percentage).



FIGURE 4: SO3 and SO4 contents in concrete mortars (expressed in weight percentage).



FIGURE 5: Optical micrograph of main minerals from concrete aggregate. Legend: Q: quartz; Q-ue: quartz with undulatory extinction angle; Mf: microcline feldspar; Pl: plagioclase feldspar; Bm: biotite mica; Mm: muscovite mica.



FIGURE 6: a) White deposits inside a pore (C1); b) White materials in the pores (C2); c) External surface of drilled core indicating several rims (C2).



FIGURE 7: Fragment of an aggregate presenting rim (C1)



FIGURE 8: Void completely filled (C2).



FIGURE 9: Massive crystals of ettringite in the transition zone (Concrete 01).



FIGURE 10: Cracked/massive gel in the whitish area from visual inspection (Concrete 01).



FIGURE 11: Rosette-like crystals of ASR next to a pore with massive gel (Concrete 01).



FIGURE 13: Agglomerates of sulfate phases in the paste (Concrete 02).



FIGURE 15: EDS spectrum of crystals from Figure 13.



FIGURE 12: EDS spectrum of ASR crystals from Figure 11.



FIGURE 14: Massive and cracked gel (rim) around aggregate (Concrete 02).



FIGURE 16: EDS spectrum of gel from Figure 14.



FIGURE 17: Grouting of microcement and epoxy resin.



FIGURE 18: Dywidag steel bars, 32mm diameter, prestressed.



FIGURE 19: Assemblage for the steel braces protection.



FIGURE 20: View of the steel braces already protected with concrete.