Diagnosis and repair of electrical transmission tower foundations affected by DEF and AAR

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Abstract

Internal Swelling Reaction (ISR) occurring in concrete elements, such as DEF and AAR, can cause stresses that easily overcome the concrete tensile strength, resulting in severe cracking. These cracks reduce the structural bearing capacity and facilitate the penetration of aggressive agents of other pathological manifestations, such as reinforcement corrosion. This work describes the appraisal and therapy of cracking occurred in the foundation structures of high-voltage power transmission towers in the Agreste region of the state of Pernambuco, in NE Brazil. A previous analysis showed that this state of degradation would have its roots in concrete swelling, which - due to the bulk of structural elements, the apparent lack of control of the production process and of an analysis of the structural designs - could have its origin in delayed ettringite formation and/or alkali-aggregate reactions. Specimens measuring 75mmx150mm were then extracted for X-ray diffractometry (XRD) and scanning electron microscopy (SEM) tests developed at the UFPB New Materials Laboratory, in order to obtain a more accurate diagnosis. The results confirmed the preliminary diagnosis: the delayed ettringite formation and the presence of silica gel in the extracted samples. The repair of structural blocks took into consideration the possibility of residual swelling and the restoration of the stiffness of structural elements. Therefore, epoxy resin injections and structural reinforcement were achieved by increasing the cross (jacketed) section on all foundation faces, using self-consolidating reinforced concrete.

***Keywords**: alkaline aggregate reaction; delayed ettringite formation; ISR; repair concrete structures; self-consolidating concrete*

1. INTRODUCTION

Internal Swelling Reactions (ISR) describe some pathological manifestations originated from internal chemical reactions occurred in the concrete, such as Alkali-Aggregate Reactions (AAR) and Delayed Ettringite Formation (DEF). Such manifestations can cause concrete elements to expand, especially in the presence of moisture. Such expansions are often associated with changes in the mechanical properties of the concrete as a result of high crack condition and may originate either from aggregates or cement pastes and result in the loss of the bearing capacity of structural elements, as well as in reduced durability. [1].

As it dates back to the 1940s and, as it is a widespread pathological manifestation with cases occurring on all continents [2], AAR has always been linked to the causes of concrete expansions, at least in structures not subject to frost actions. However, since the 1980s [3], in some ISR cases, the presence of ettringite crystals filling both the interfacial transition zone between the aggregate and the cement paste, as well as microcracks, has also been observed, which cast doubts regarding the cause of such expansions.

Since then, several surveys have been carried out worldwide to check if delayed ettringite formation could also be an agent causing expansions in concrete structures. It was noted that DEF was linked to: high temperatures during the concrete curing period, high SO_3 and Al_2O_3 contents in cement, and the high relative humidity with levels close to the saturation of the material [4]. Some authors [5-7] regarded these conditions as required - yet not sufficient - for the occurrence of such expansions because, for instance, expansions in cement pastes are much less prominent than in mortars and concretes and mainly due to the situation observed by Collepardi [5], who realized that pre-cracked structures had a greater tendency to the delayed ettringite formation and even greater expansion.

Therefore, the technical-scientific environment has conducted many discussions, leading to the emergence of two schools of thought. The first one was formed by those who believe that ettringite is not directly responsible for internal expansions in concrete, and that recrystallization occurs as a result of the empty spaces left by uniform expansions of the cement paste when subjected to high curing temperatures, or even by cracks caused by other pathological manifestations, in particular AAR, [6]; and those who believe that the recrystallization of ettringite can generate stresses high enough to expand concrete elements and cause degradation states.

Supporters of the uniform cement paste expansion explained that portions of delayed formed ettringite crystals uniformly fill the interfacial transition zone between the aggregates and the cement paste, and that the width of such formations are proportional to the size of the aggregates, indicating that the cracks were not caused by DEF but that these formations recrystallized in the empty space [8], and that the growth of ettringite crystals cannot generate enough tension to crack the concrete. Therefore, the occurrence of ettringite crystal formations in cracks would rather be a consequence - and not a cause - of the cracks.

On the other hand, the group of researchers who believe that concrete expansion resulting from the formation of the delayed ettringite crystals seems to be more numerous and have more solid arguments. Diamond [3] criticizes the hypothesis of uniform paste expansion, demonstrating through some studies that expansion is not uniform. Also, according to Diamond and Taylor [3, 6], they demonstrated through the concrete fracture mechanics that the tensions required to generate expansions in the concrete from empty spaces or microcracks are not that high and are compatible with DEF-caused tensions. Taylor [6] quoting other authors, developed a study that would ensure DEF as the only possible cause of expansion in mortar bars subjected to high curing temperatures and, as a conclusion, expansion states were identified in those samples.

The fact is that the mechanism by which DEF-caused expansions occur is still not quite well understood [3]. Also, there is no consensus in the technical-scientific milieu that DEF could be considered a primary or secondary cause of expansions in concrete structures. However, Hasparyk [9] realized that structural elements affected simultaneously by the occurrence of DEF and AAR can show highly advanced degradation states. This study demonstrates the concomitant occurrence of DEF and AAR in structural elements in the foundation of electric power transmission line towers diagnosed through X-ray Diffractometry (XRD) microstructural analysis and Scanning Electron Microscopy (SEM), also including a chemical analysis conducted using energy-dispersive X-ray Spectroscopy (EDS) in samples extracted from such these elements, as well as a therapy carried out in the repair and reinforcement of such structures.

2. CHARACTERIZING STRUCTURAL ELEMENTS AND SYMPTOMS

Along high-voltage electrical power transmission lines, supporting structures serve to provide uphold to lightning rods and conductors and are designed to support the loads and transmit them to the foundations. These supporting structures are generally formed by latticed towers with metallic frames, concrete or wooden poles, [10]. The lines usually stretch over hundreds of miles and cross the most varied climates and environments; they often power several states of the Federation, and the distances between the support towers may vary from a few feet to almost one mile, which indicates that these structures are subject to the most varied types of foundation settlement soils and types of environments.

The foundations of transmission line support towers tend to be components subject either to tensile or compression strengths, which confers a specific geometric characteristic, usually with heavy mass and a wide base, so that the soil plays a role in resisting the tensile strengths.

Figure 2.1: Transmission line tower with supports

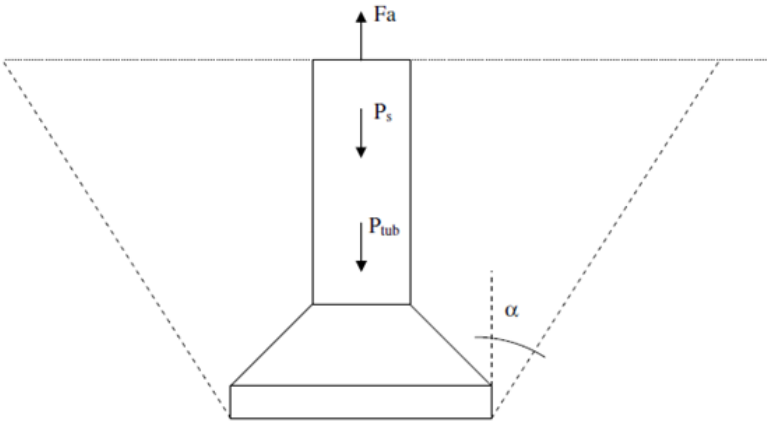

Figure 2.2: Foundation layout of a transmission line supporting tower

During routine inspection activities at the structures that comprise electric power transmission lines, technicians from TAESA (Transmissora Aliança de Energia Elétrica SA), which holds the NTE concession for the distribution of high-voltage electricity, identified between 2017 and 2018 an increasing state of degradation of foundation elements of support towers, especially in the surroundings of the Angelim II substation located in the city of Angelim/PE, which is one of the most important ones in the region.

The Angelim II substation is managed by the local state-owned distribution company and accessed by TAESA; it also belongs to the national interconnected system as one of the main supply trunks in the NE of Brazil. The transmission lines that are the object of this work included the LT230kV Campina Grande II and LT500kV Xingó/Angelim II lines, measuring 188.4 km and 192.6 km, respectively, and originating from the Angelim II substation.

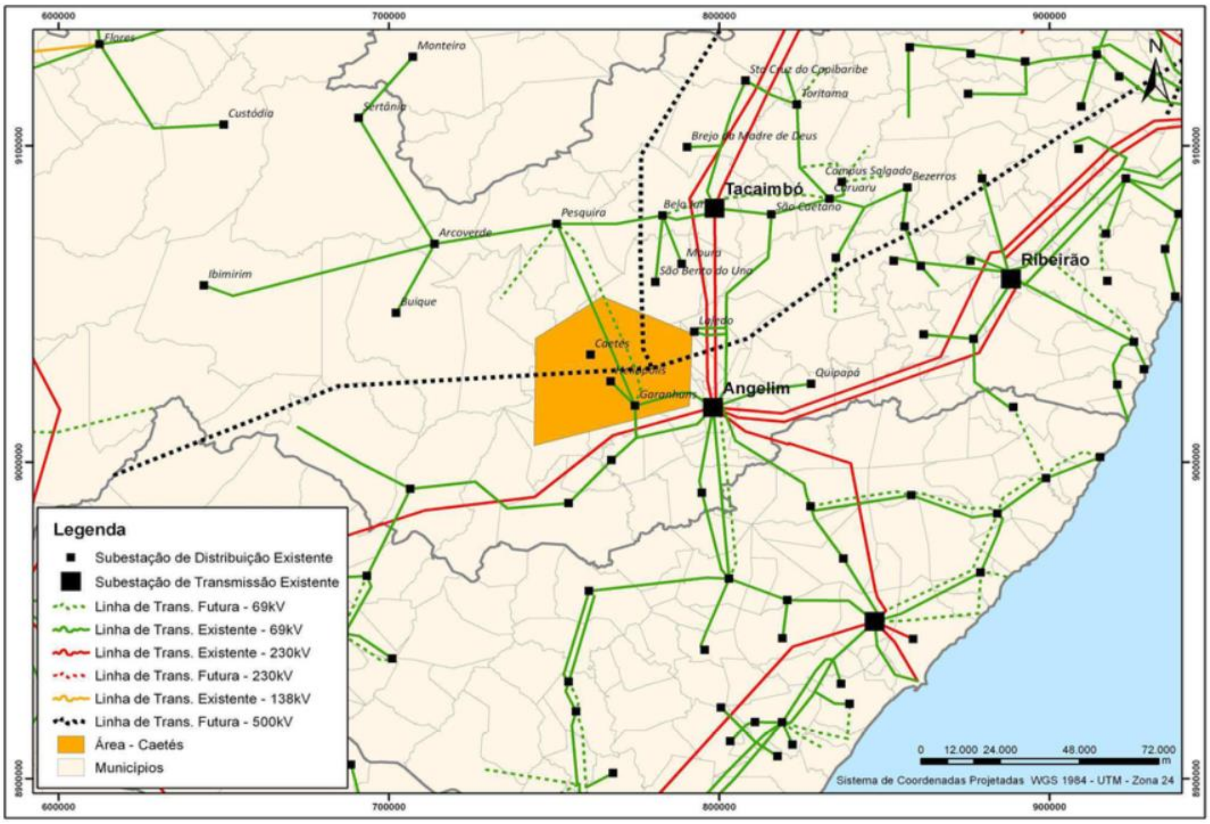

Figure 2.3: Map with the location of substations and transmission lines in the surroundings of Angelim/PE

The most common symptoms on the related elements were geometric cracks mapped over the entire length of the foundation element, which varied between 0.5 mm and 3.0 mm in width; stains due to efflorescence (leaching of calcium hydroxide).

Figure 2.4: Images of the foundation element of supporting tower 003 (Foot B) of the LT500kV Xingó/Angelim II-line (a) overview of the cracks (b) detail of crack width

3. DIAGNOSIS

Along the lines, the entire deployment section of support towers such as the LT230kV Campina Grande II and LT500kV Xingó/Angelim II lines was initially inspected during a technical visit to confirm, catalog and record any degradation symptoms. Interviews with employees were conducted, documents (structure designs, service letters, maps, maintenance plans, construction process documents) were analyzed in order to obtain as much useful information as possible.

The information obtained indicates that the support towers had a wide range of construction ages, between 10 and 35 years. It was also noticed that several companies performed the building activities and, as a consequence, the construction processes and the materials used varied a lot.

In view of the data and information obtained, a preliminary diagnosis was discussed with the participation of the company that held the concession, in order to create a plan of attack for carrying out an inspection on the structures by considering the several likely occurrences.

Some support towers showed wider cracks and an age of construction of 10 years, although some others were over 30 years of age. The cracks on other towers seemed to be superficial, despite the age of construction dating back to more than 30 years. In most cases, the cracks had a mapped geometry, were 2mm wide and penetrated about 100mm into the structural element.

Then, cylindrical samples with a diameter of 75 mm and height of 150 mm were extracted from the concrete on the upper faces of the foundation elements of the transmission line support towers, either from structural parts with a 10-year construction age, or from structural elements with an older construction age, so that tests could be performed and confirm the preliminary diagnoses. In the extracted samples, microscopic analyzes were performed using X-ray Diffractometry (XRD) and Scanning Electron Microscopy (SEM), including a chemical analysis using energy-dispersive X-ray Spectroscopy (EDS). The tests were carried out at the New Materials Laboratory (TECNOMAT/UFPB) of the Paraíba State Development Institute - IDEP of the Universidade Federal da Paraíba (Federal University of Paraíba).

The samples were extracted for each construction age condition from foundation elements at different areas far from compression zones, by considering both the distance of the tower feet and the depth and lateral distance of the top surface; then they were isolated with a PVC film and sent to the Laboratory. Each sample was further divided into four parts height wise; each part being named T1-1, T1-2, T1-3 and T1-4.

The X-ray diffraction tests were performed using a Panalytical BRUKER D2 diffractometer (with real-time multiple Lynx Eye detector) operated using Cu K (X radiation at 30mA and 15 kV). They showed the presence of the following minerals: quartz (Q), portlandite (P), calcite (C), and ettringite (E) in all samples analyzed in all diffractograms. Such occurrences can be seen in the diffractometric pattern shown in Figure 3.1, with special attention to the presence of ettringite. Such occurrence should be highlighted, since this mineral appears in a smaller volume when compared with the other minerals present in the concrete.

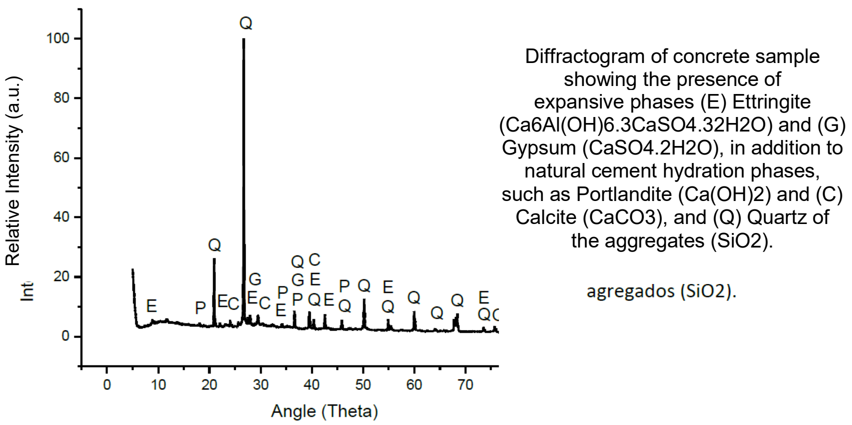

Figure 3.1: Concrete diffraction pattern

The use of SEM/EDS detected a silica gel formation. Given the amorphous or semi-crystalline nature of the deposits, such detection could not be effectively performed with XRD. The images show the presence of the gel either around the coarse aggregate, or inside the aggregate; the crack condition originating from coarse aggregates, in addition to the wear of the coarse aggregates themselves, also confirm that the AAR caused the concrete of the foundation elements of the transmission line support towers to expand.

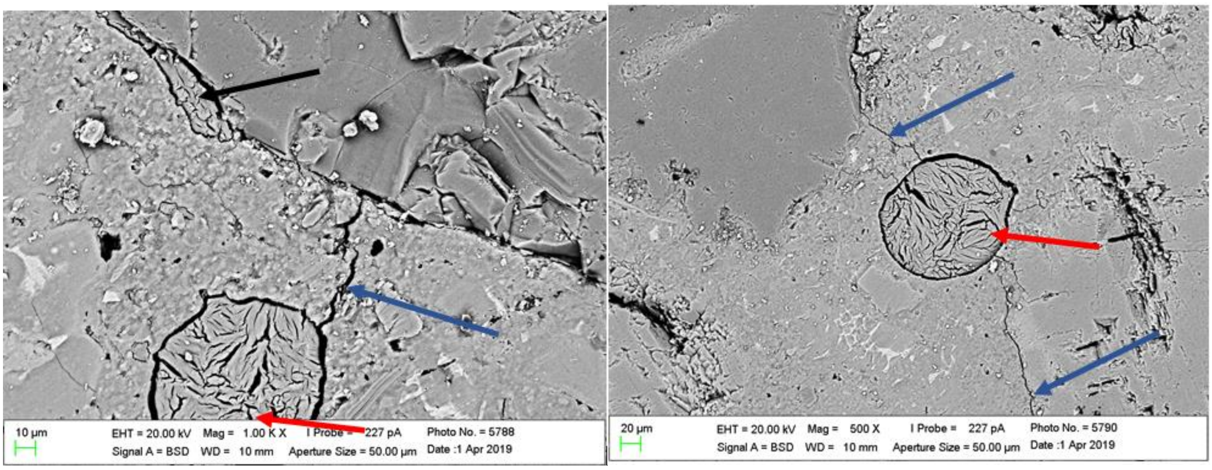

Figure 3.2: SEM analysis - silica gel (black), ettringite (red) and cracks (blue)

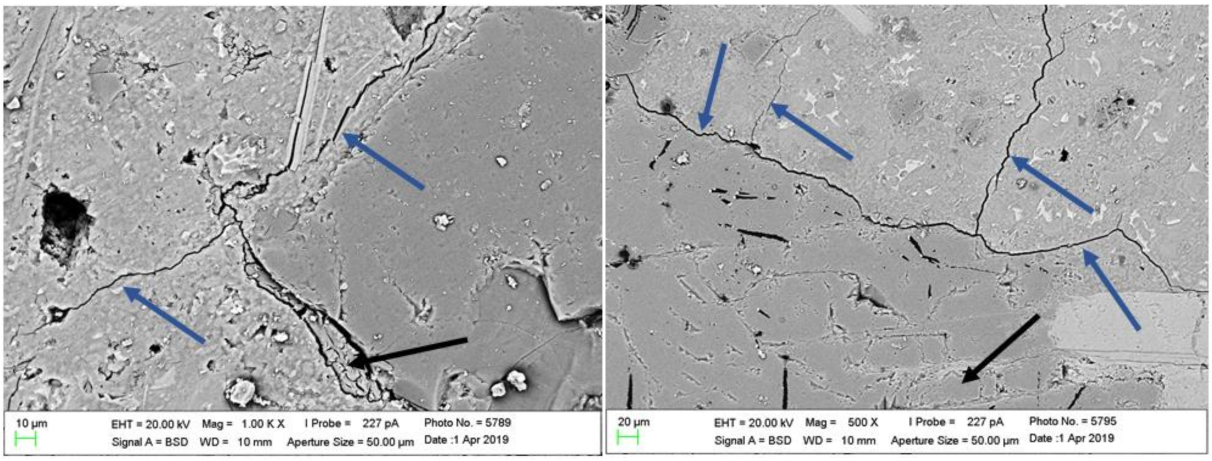

Figure 3.3: SEM analysis - silica gel (black), ettringite (red) and cracks (blue)

Confirming the results obtained in the XRD, the images show massive deposits of ettringite located at empty spaces in the cement matrix and a high concentration of cracks originating from such deposits, in addition to the morphology of the cracked phase, which indicate that the mineral underwent a delayed formation - thus confirming that DEF was, at least one cause of the expansions observed in the foundations analyzed.

4. REPAIR AND REINFORCING STRUCTURES

A system comprising the repair and reinforcement of reinforced concrete structures of the foundations of transmission line support towers was proposed, the primary objectives of which included: restoring the stiffness (Young modulus) of the structural elements and preventing or minimizing residual expansion. Secondly, the reinforcement and repair activities of the foundation elements would also bring additional benefits, such as: for instance, preventing the crack condition of the elements from causing other pathological manifestations, such as the corrosion of rebars; providing greater protection against the weather by protecting the existing structure with a less porous material; and increasing the bearing capacity of the existing foundations.

The repair and reinforcement solution would work in two lines of action: injecting an epoxy resin into the cracks to restore the monolithic characteristic of the concrete and its consequent stiffness; and reinforcing the foundations by incorporating passive rebars to restraint the foundation element and prevent or minimize any additional expansion, since, as by some authors [11-16] point out, expansion in structural elements struck by ISR is reduced or even eliminated when restraint stress are imposed. The use of prestressed concrete was also considered as a solution to confine concrete swelling;

however, given the possibility and even the expectation of additional expansion, which would require greater control of the post-tensioning, this solution was discarded.

The reestablishment of the stiffness of the foundation element would ensure that the operating loading actions could respond to the answers foreseen in calculations from the strain and displacement perspectives, because transmission line support towers have several elements that could be affected by an excessive displacement of the structure, thus causing a shortage of electricity supply.

On the other hand, the steel reinforcement restraint stresses the foundation elements would operate as a restriction to additional expansions of the elements, since some foundation elements have already shown the presence of silica gel and the construction ages of which were not too old; this created an expectation that alkali-aggregate reactions could still occur, generating more expansion and cracks. Even older foundations could still develop residual expansions due to AAR.

Some authors who studied the swelling confine in concrete subject to AAR found that the final free expansions in concrete or mortar elements were always less than 1% ([20] <0.70%; [19] <0.90%; [12] <0.80%; [16] <0.35%; [17] <0.60%), this value was extrapolated to foundations elements final expansion in present work, considering that residual expansion tests, such as those proposed by the classical methodologies to measure residual expansion value in concrete affected by AAR, were not carried out, given the concretes high heterogeneity used; the different shapes and geometry of structural elements; the different rebar rates and arrangement, which would cause high anisotropy levels and high scatter information.

Still, Multon [16] evaluated the residual concrete expansion affected by AAR, considering some variables: concrete age, concrete saturation levels, structure casting direction and among the conclusions, maximum residual expansion obtained was 52% in relation to final expansion, taking into account situations that are much more adverse than would occur in real foundation elements towers evaluated here.

With these parameters - final expansion and residual expansion - the reinforcement rebars were dimensioned using, for this purpose, the Anchorage Zone Method exposed by Fusco [21], which aims to determine the transversal reinforcements to resist the tangential efforts as a result of the residual potential of expansion, in the particular case of partially loaded foundation elements. The transversal stresses induce longitudinal cracking in foundations blocks that are resisted by reinforcement calculated in each dimension by:

$$A_{st} = 0,3\left(1 - \frac{a_0}{a}\right)\frac{F_{cod}}{f_{yd}} \qquad (1)$$

Being: A_{st} as steel area anchorage; a_o as column dimension; a as block dimension; F_{cod} as design load; f_{yd} as steel yield strength. The calculation load was obtained by analyzing the deformations imposed by the expansion caused by the AAR.

The work would primarily consist of injecting a low viscosity epoxy resin with a high-pressure device (22,5 MPa) and applying a 10 cm wide layer of reinforced concrete, which would jacket the foundation element designed to generate a restraint stress and restricting internal swelling. In a restricted structure, passive rebars and self-compacting concrete with characteristic compressive strength of 60MPa would be used.

The concrete repair and reinforcement activities took place at 39 foundations of support towers of the LT230kV Campina Grande II and LT500kV Xingó/Angelim II transmission lines. The most distant blocks were approximately 62 miles (100km) away from the Angelim II substation, the city chosen for the installation the building site.

The operating and managerial processes were then defined based on the logistics required to carry out the activities: a concrete batching plant, a central building site, advanced workstations, location of support towers. Field activities were broken down according to the expertise of the teams formed: preliminary service team, foundation element excavation and cleaning team, crack identification team, resin injection team, rebar team, formwork team, concrete team and, finally, a backfill team.

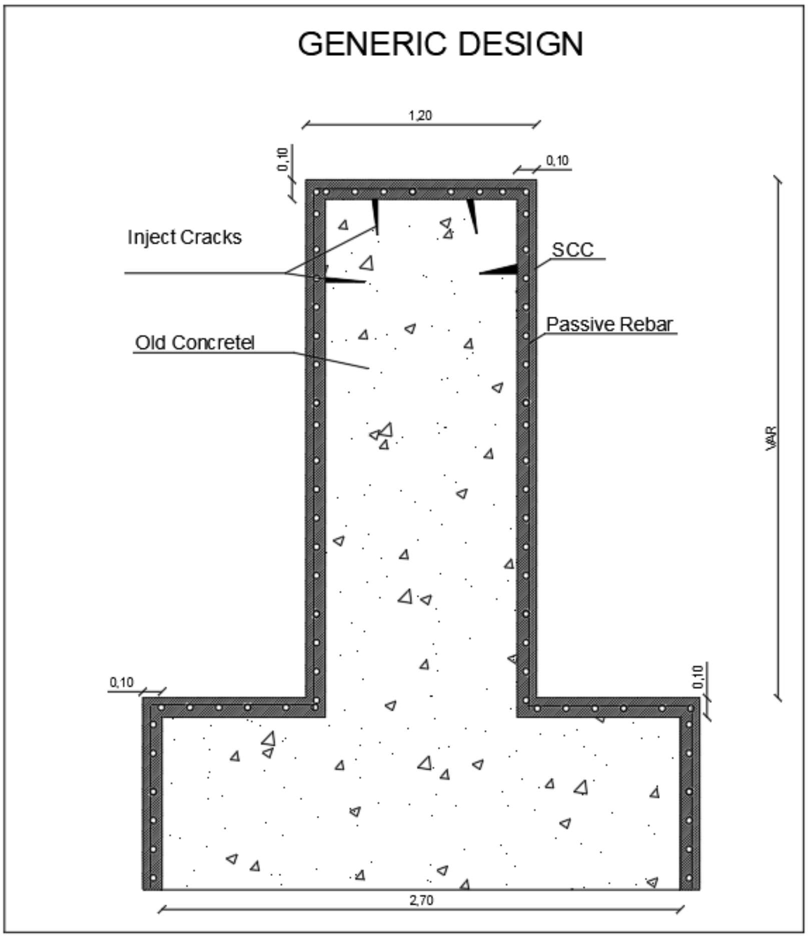

Figure 4.1: Generic detail proposed for the recovery solution and structural reinforcement of the foundation elements of support towers

Figure 4.2: Nozzle installation sequence: (a) drilling and dry cleaning; (b) applying the nozzles; (c) sealing the crack surface with thixotropic epoxy resin

Figure 4.3: Assembling reinforcement rebars for the foundation elements

The choice for self-compacting concrete was due to the small wide layer of reinforced concrete (10cm) and the high concrete drop height, so the need for a highly cohesive concrete. The materials utilized in the concrete - fine aggregate and coarse aggregate - were not tested for reactivity, thence the high cement replacement content with added silica fume, which is a pozzolanic material with low aluminate and alkali contents. A concrete composition was also dimensioned to reduce the aluminate and alkali contents in the mixture and the alkali content of the concrete, given that the region is famous for having various aggregates identified as potentially reactive.

Table 4.1: Composition of self-consolidating concrete

Item	Description	Apparent Density kg/dm³	Density kg/dm³	Mass/m³ (kg)
1	Cement CPII - F (NBR 16697)	1,025	3,150	351,789
2	Silica fume	0,890	2,200	49,792
3	Medium River Sand - specifc sample	1,410	2,630	952,536
4	Quartzite Gravel - specifc sample	1,430	2,650	676,517
5	WVA	1,000	1,000	123,126
6	Polycarboxyl Ether Superplasticizer	1,070	1,070	7,577
7	Mid-range Superplasticizer	1,030	1,030	5,412
8	Water	1,000	1,000	162,364
Total				**2.329,114**
Water/binder rate		0,462		
Mortar percentage		0,581		
Coarse aggregate/fine aggregate rate		0,710		
Total aggregate percentage		69,943%		
WVA percentage		35,000%		
Mid-range Superplasticizer percentage		1,348%		
Cement substitution percentage		14,154%		
Polycarboxyl Ether Superplasticizer percentage		1,887%		

Figure 4.4: (a) Concrete work, (b) and (c) concreted foundation element

Figure 4.5: Concreted foundation elements (a) and (b)

5. FINAL CONSIDERATIONS

Alkali-Aggregate Reactions and Delayed Ettringite Formation are two important pathological manifestations affecting reinforced concrete structures, especially more massive structural elements and more subject to the action of humidity, like the foundation elements of a structure also are.

The parallel occurrence of these pathological manifestations, although more difficult, has been reported in several cases already registered around the world. The consequence of this joint action can be much more harmful to the concrete, because in addition to two sources of expansion, the initial DEF action, for example, potentiates the expansions caused by AAR, due to the possibility of increased internal humidity in the concrete that penetrates through the cracks, among others. Another point worth mentioning is that the repair and structural reinforcement technique adopted when expansions originate from two different causes should consider that expansions occur at different times in the structure's life and with different degrees of displacement.

The structures that underwent intervention - 39 foundation elements in total - are only a small portion of the total foundations that cracked along the two transmission lines in question. Preliminary investigations point out that the total foundation elements can exceed 800 units.

A precise and concise diagnosis of the causes, origins and mechanisms of pathological manifestations is key to determine the technical techniques for repairing and reinforcing the structures as required, so as to guarantee efficient treatment, an efficient consumption of resources and durable solutions, considering the large number of elements that need intervention. The use of advanced techniques such as XRD and SEM/EDS has proven to be highly effective for a better diagnosis.

Also considering the negligence in the construction process of such structural elements and the large number of reactive aggregates throughout Brazil, it is not an exaggeration to imagine that internal expansions in the concrete present in the foundations of transmission line support towers are an even more comprehensive issue.

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