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Sulfate attack of concrete building foundations induced by sewage waters

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Abstract

A case history of a severe degradation of concrete foundation plinths and piers of an about-35-year-old building located in Northern Italy is described. Significant amounts of gypsum, near ettringite and/or thaumasite were detected by X-ray diffraction analyses performed on ground concrete samples. Large gypsum crystals were mainly located at the interface between the cement paste and aggregates, as observed by scanning electron microscopy coupled to energy-dispersive spectroscopy microanalysis. The degradation effects increased with decreasing the distance of concrete structures from an absorbing well located in the courtyard of the building. The well was recognized as the sulfate source due to the microorganism metabolism of sulfur compounds present in the sewage. Consequences of this attack were a very poor bond strength between cement paste and aggregates and a severe cracking of the concrete cover of the steel reinforcement. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Degradation; Sulfate attack; X-ray diffraction; SEM; EDX

1. Introduction

A building about 35 years old, located in the suburbs of Torino (Northern Italy), presents a severe degradation of concrete foundation plinths and piers, from the plinth level up to 2 m. However, the degradation does not affect all the foundation structures in the same extent, but it seems more severe in the plinths and piers located close to the internal courtyard of the building and the deterioration effects decrease with increasing the distance from the ground level. The bond strength between the cement paste and aggregates is poor, and the concrete cover of the steel reinforcement is, in many cases, cracked or even spalled off (Fig. 1). Consequently, the metallic reinforcement is significantly corroded.

In searching for the possible causes of degradation, firstly, the geological map of the soil, on which the building insists, has been analyzed. It clearly appeared that this soil does not contain gypsum or other sulfate-based minerals and it was never crossed by industrial waste waters. However, since the building was located outside of the limits of the urban sewage system, temporarily an absorbing well was used for collecting sewage. This was 8 m deep, located in the internal courtyard at about 9 m from building foundations. After then, it was disused but not completely eliminated. An inspection demonstrated that stagnant water was still present on its bottom. This paper deals with the case history to illustrate how concrete was subjected to sewage attack.

2. Methods

Because of the extensive concrete degradation, some preliminary rebound hammer tests were carried out on the foundation plinths and piers to identify some representative sampling points. After that, sound concrete samples were collected from plinths and at different heights of the piers, namely at 1 and 3.5 m from the plinth. Coring was unsuccessful due to the low concrete strength and, therefore, the samples were collected by using a metal chisel on the concrete from the sampling surface to about 100 mm in depth. The schematic map of the building showing the details of the sampling points is shown in Fig. 2. Samples were collected from plinths P_1, P_2 and P_4, and from piers from P_1 to P_8.

Each concrete sample was entirely ground in a ball mill and then analyzed by X-ray diffraction (XRD), whereas

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Fig. 1. Example of severe degradation of concrete and steel reinforcement of the building foundations: P_2 pier.

scanning electron microscopy (SEM) observations coupled to microanalyses by energy-dispersive spectroscopy (EDS) were carried out on the collected samples without grinding. Concrete samples were also dispersed in distilled water neutralized at pH of 7. After 2 h of contact under continuous stirring, the suspensions were filtered and measurements of pH and electrical conductivity were performed on the clear water solutions.

3. Results and discussion

By a visual inspection of the foundations, a qualitative scale of degradation was defined: the most severe deterioration occurred in plinths and piers P_1 and P_2; the deterioration degree was lower in P_3, P_4 and P_5, whereas piers P_6, P_7 and P_8 were almost intact. However, in all cases, poor quality concrete was observed, with significant aggregate segregation at the bottom of the piers. These observations, combined with the rebound hammer test results, clearly indicated two trends. First, concrete strength increased from the plinth to the higher part of the piers and, second, the lowest values were recorded on the plinths located in the proximity of the absorbing well. Strength values of 10–12 MPa or less were measured on the plinths and on the bottom of piers P_1 and P_2, whereas at a height of about 2.5 m from

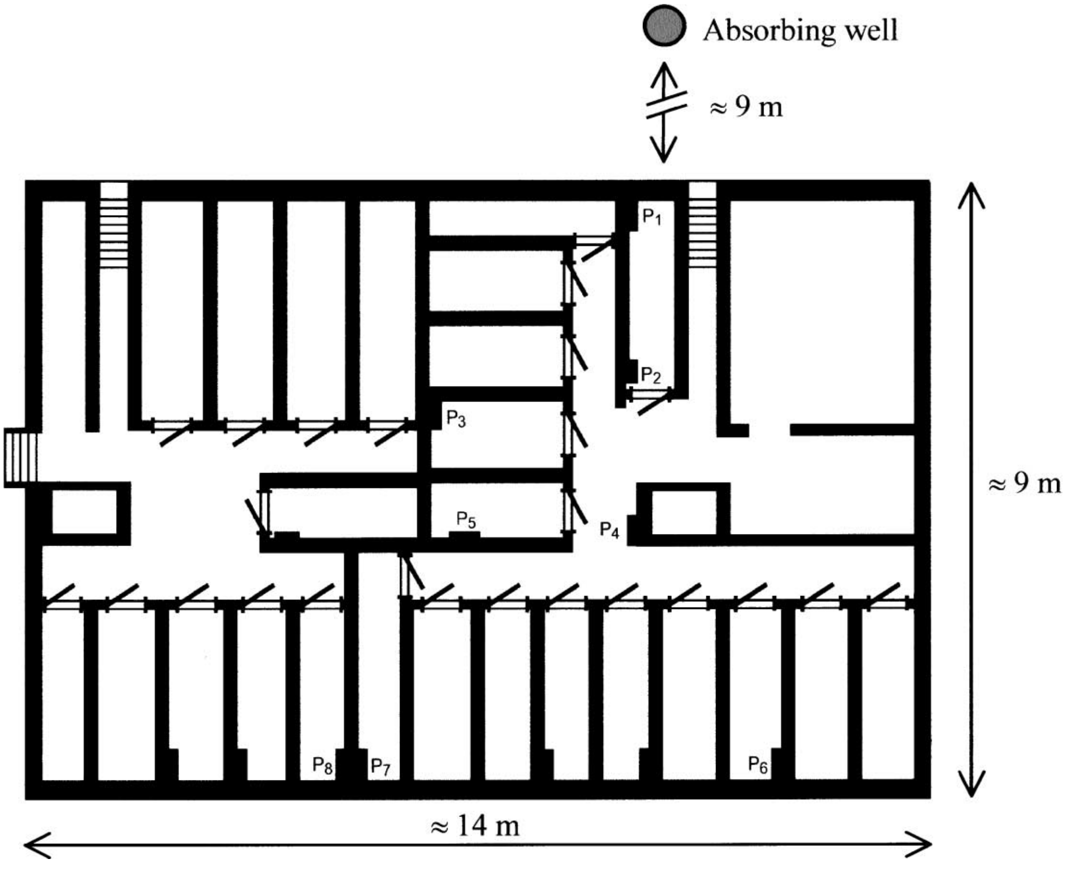

Fig. 2. The map of the investigated building with the details of the sampling points (P_1–P_8) and the location of the absorbing well.

the plinth, they still showed strength values of 15–18 MPa. The piers slightly affected by this degradation (i.e., P_6, P_7 and P_8) presented strength levels of 35–40 MPa. In addition, the plinth samples were extremely wet. A mass loss of 15% after drying at 105 °C was measured on the P_1 plinth, and the mass loss decreased to 12% and 5%, in the P_2 and P_4 plinth samples, respectively. This trend can be probably ascribed to a preferential groundwater flow moving from the internal courtyard of the building, favored by a slight soil slopeness.

Very dispersed data resulted from pH and conductivity measurements. However, also in this case, a trend was clearly observed. The slightly deteriorated samples showed the higher pH values (usually higher than 8). On the contrary, a typical "knee" trend for both pH and conductivity data was observed in the samples from deteriorated structures such as the P_1 sample (Table 1): at 1 m, there is a minimum in the pH and a maximum in the electrical conductivity.

From XRD patterns of the samples collected from P_1 plinth and pier, the typical products of a sulfate attack were clearly identified. The most interesting part of the patterns is reported in Fig. 3. Gypsum was detected only in the sample collected at a height of 1 m from the plinth, whereas small amounts of ettringite/thaumasite were present in all P_1 samples (from the plinth, at a height of 1 and 3.5 m, respectively, from the plinth). Also in this case, the amount of the sulfate-based products decreased by increasing the distance of the sampling point from the absorbing well. In fact, the XRD patterns of the P_2 samples were similar to those of the corresponding P_1 samples, whereas only traces of gypsum were detected in the samples from P_3 to P_5. Any evidence of the above products was in P_6, P_7 and P_8 samples. XRD patterns also presented the prevalent peaks of silicate aggregates, whereas peaks of carbonate aggregate were identified only in very few cases independently of the collecting zone.

The SEM observations confirmed the XRD data. The P_1 plinth sample showed only limited regions affected by gypsum and/or ettringite, even if it appeared to be highly porous and cracked. Frequently large voids were observed all along the transition zone between cement paste and aggregates (Fig. 4). The aggregate surface seemed to be almost clean: only very few cement paste particles remained attached on it due to their poor adhesion or even to dissolution of a preexisting interfacial phase. In the 3.5-m sample, neither gypsum nor ettringite nor thaumasite was identified, whereas the 1-m sample was significantly affected by the presence of gypsum, sometimes growing as long rams horn-shaped grains (Fig. 5), very similar to the fibrous crystals of Satin spar mineral [1]. A low-magnification image of the contact region between quartz aggregate and columnar gypsum crystals is shown in Fig. 6. In all cases, the phase composition was determined by EDS analyses. Very frequently, the growth of gypsum crystals at the transition zone between cement paste and aggregates led to a partial or almost com-

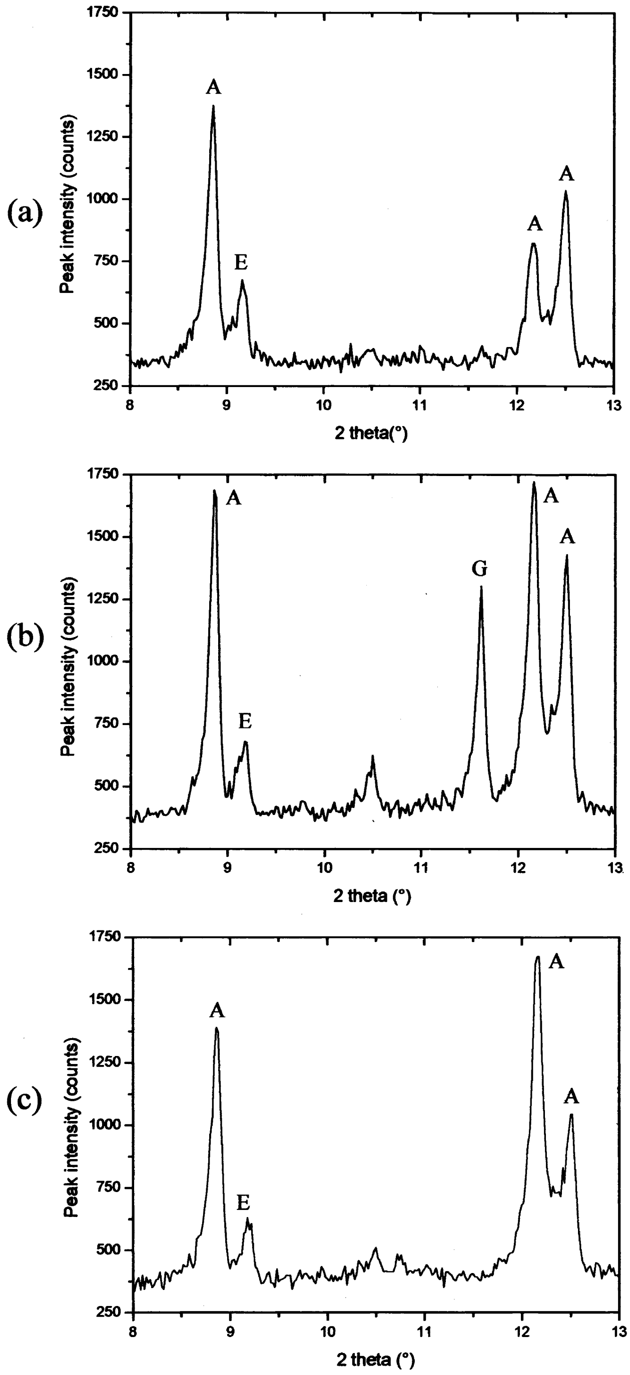

Fig. 3. XRD patterns of degraded concrete P_1 samples: (a) plinth sample; (b) sample collected at a height of 1 m from the plinth; (c) sample collected at a height of 3.5 m from the plinth (A = aggregate: mica and potassium aluminium silicate; E = ettringite/thaumasite; G = gypsum).

Table 1
The pH and conductivity values of the water solutions obtained by dispersion of P_1 samples in distilled water at pH 7 and subsequent filtration

P_1 concrete sample	pH	Conductivity (μS)
Plinth	7.5	305
At a height of 1 m	7.2	1650
At a height of 3.5 m	8.1	160

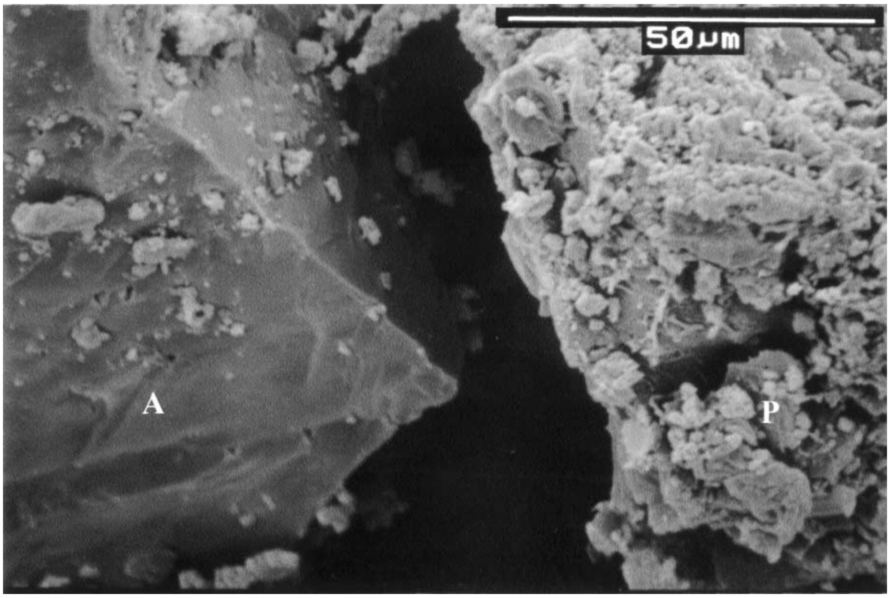

Fig. 4. SEM image of a large void between quartz aggregate (A) and cement paste (P) in P_1 plinth sample.

plete detaching (Figs. 7 and 8) between cement paste and aggregate, which should be responsible for the significant strength loss. Gypsum was only sometimes detected in the cement paste.

From the above results, it clearly appears that the concrete was severely damaged by a sulfate attack, which led to the formation primarily of gypsum, with smaller amounts of ettringite and/or thaumasite. Since sulfates were neither originally present in the soil nor brought from industrial waste waters, their origin can be ascribed to the presence of the absorbing well. In fact, it is known [2–4] that sulphur compounds present in the sewage are reduced by microorganisms to sulphides where anaerobic conditions prevail.

Some of the sulphides can escape as hydrogen sulphide gas, which dissolves in the atmosphere moisture and condenses on the walls of the well. Here, H_2S is converted by sulphur-oxidising bacteria to sulphuric acid. This phenomenon is increased by slime stagnation, which provides an excellent breeding ground for sulphide-producing organ-

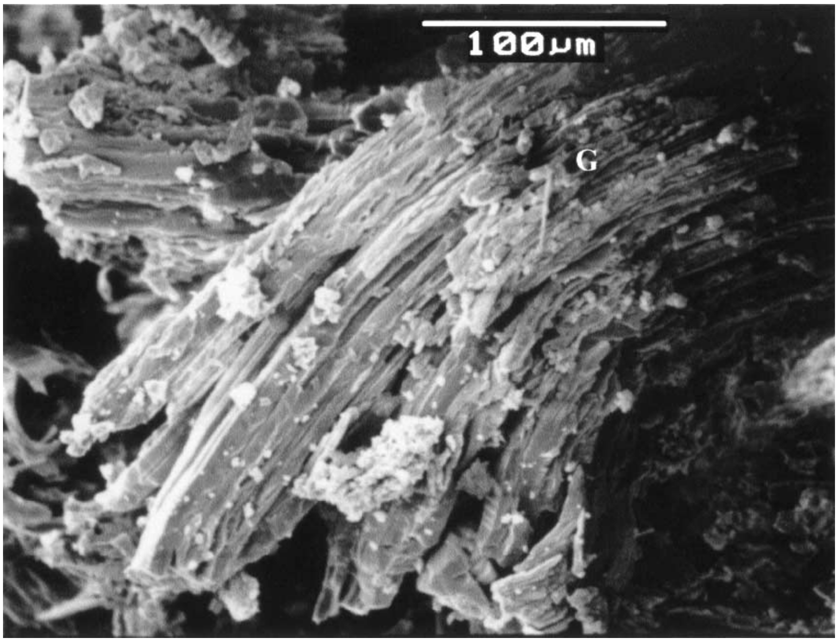

Fig. 5. SEM image of some horn-shaped gypsum crystals (G) grown in the P_1 sample at a height of 1 m.

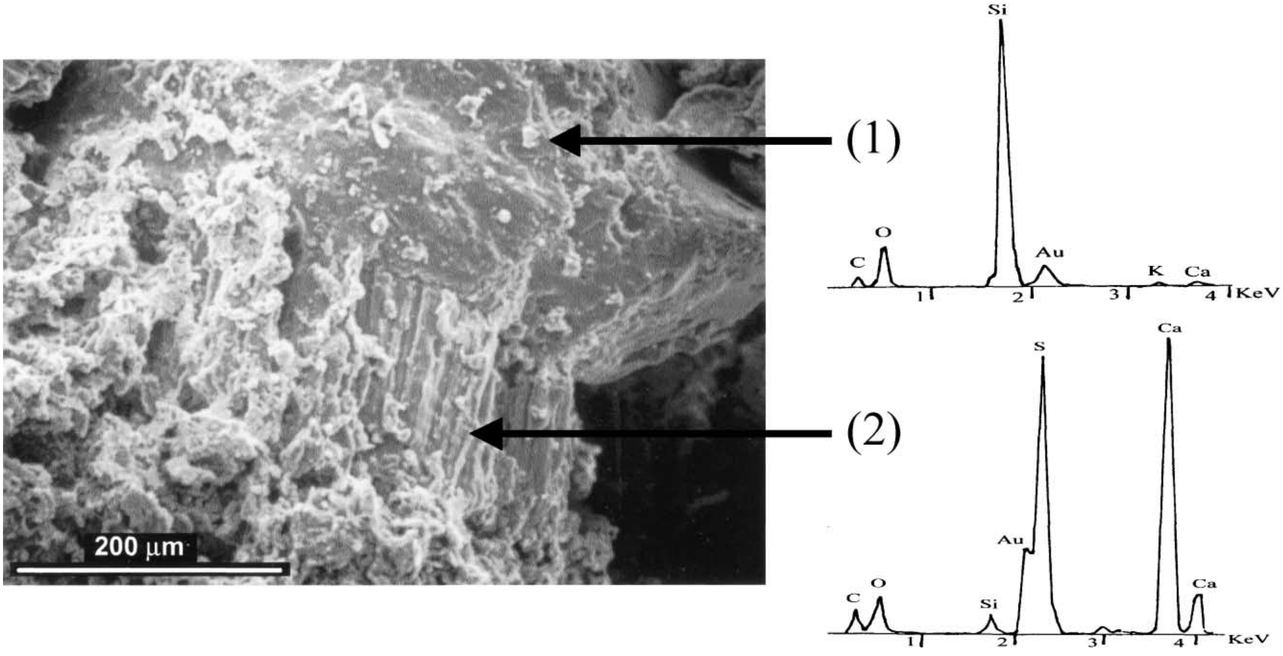

Fig. 6. SEM micrograph, combined with EDS analyses, of a degraded concrete P_1 sample at a height of 1 m: point (1) quartz grain; point (2) gypsum crystals.

isms. The most severe attack was consequently observed on the walls of the well and, after that, on the nearest plinths and piers of the building. In fact, the waste waters collected in the well and progressively acidified by the yielded sulphuric acid moved to the building foundations due to a favourable ground structure.

Deterioration of concrete by sulphuric acid produced from sewage is a long-term process, but poor-quality concrete, as is the studied case, deteriorates at a much faster rate than good-quality ones [5]. In addition, when a sulphuric attack is active, under a very low pH, all hydrated products, hydrated silicate and aluminate phases and calcium hydroxide can easily be decomposed, leading to a severe disintegration of the concrete matrix [6–8]. In fact, as previously stated [9,10], in this case, the ettringite expansion phenomenon alone is inadequate to explain the sulfate-generated deterioration of the concrete.

The strength loss recorded through the rebound hammer test measurements can be related to the decalcification [7,8,11] of C–S–H to form either gypsum ($C\overline{S}H_2$) or thaumasite ($CS{\cdot}C\overline{S}{\cdot}C\overline{C}{\cdot}H_{15}$) according to reactions (1) and (2):

$$\begin{matrix}CH\\ C-S-H\end{matrix}\ \xrightarrow[H_2O]{SO_4^{=}}\ C\overline{S}H_2 \tag{1}$$

$$\begin{matrix}C-S-H\\ CH\end{matrix}\ \xrightarrow[H_2O]{SO_4^{=},CO_3^{=}}\ CS\cdot C\overline{S}\cdot C\overline{C}\cdot H_{15} \tag{2}$$

Sulfate attack based on the decalcification of C–S–H with formation of gypsum according to process (1) and loss

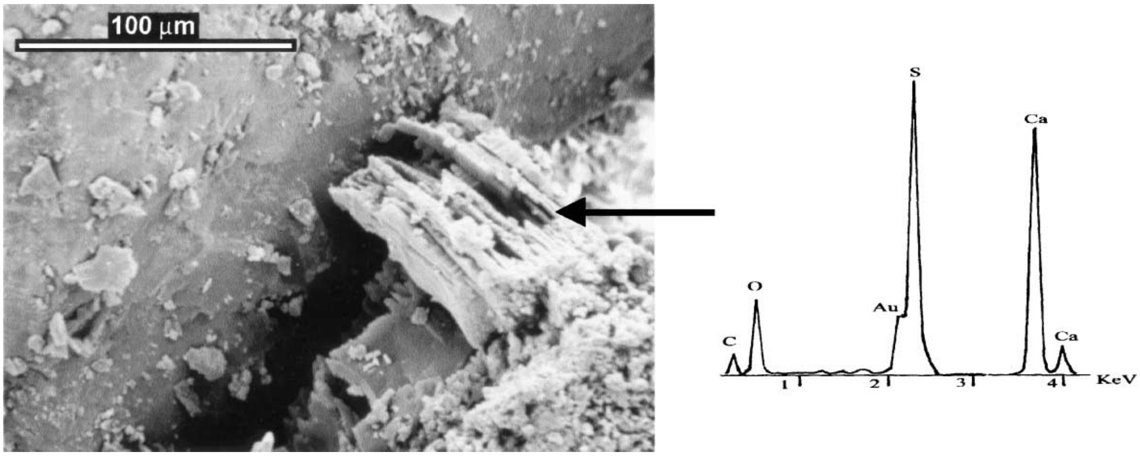

Fig. 7. Detail of the transition zone between cement paste and quartz aggregate in P_1 sample at a height of 1 m: gypsum crystals growing at this interface, as detected by EDS.

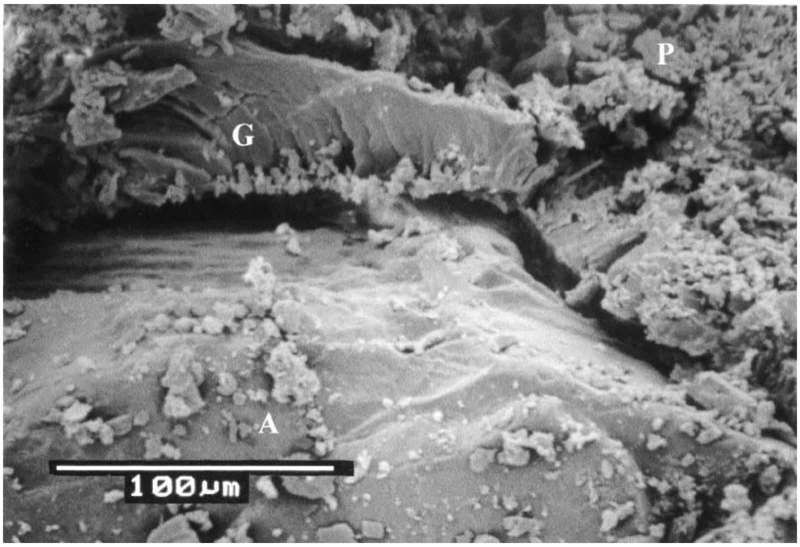

Fig. 8. P_1 sample at a height of 1 m: debonding at the transition zone between cement paste (P) and quartz aggregate (A) due to a large stack of gypsum crystals (G).

of both strength and adhesion of the cement matrix has been found by Mehta [10] and Collepardi [11,12]. On the other hand, the decalcification of C–S–H related to thaumasite formation according to process (2) appears to be even more severe than that of process (1). This process was found in some repairing works of historical buildings where gypsum existing into the walls of these structures reacts with Portland cement used as repairing material [13].

The explanation that gypsum was mainly located at the interface between the cement paste and aggregate lies in microcracks originally present in the transition zone between the aggregate and the cement paste. These cracks are larger in width than most capillary pores in the cement paste and, therefore, they can act in establishing interconnections, which increase the permeability of the system [14].

The evolution of gypsum amount in the above plinth and pier (a low gypsum content detected in the plinth and higher values at a height of about 1 m from it) can be reasonably imputed to the work stoppage of the well after about 15 years from the building construction. The well was neither drained nor filled up by ground. Therefore, it was still active in keeping wet the building foundations. The previous severe sulfate attack made the plinth concrete more permeable, allowing the water to rise higher and higher in the pier. Multiple dissolution–precipitation steps of gypsum due to water evaporation at increasing height in the pier can explain the present distribution of gypsum amount, which shows a typical "knee" trend already observed, for instance, in the case of the content of water-soluble salts in masonry as a function of height [15]. The dissolution of the gypsum yielded by the sulfate attack at the interface between the cement paste and quartz aggregate is in fact well evidenced in the P_1 plinth micrographs (see Fig. 4). On the contrary, the enrichment in gypsum in the sample collected at a height of 1 m, in the same pier, was demonstrated both by XRD and SEM analyses (see Figs. 5–8).

4. Conclusions

A case history of sulfate attack by sewage on the foundation plinths and piers of a concrete building in Torino, Northern Italy, has been reported. Inspections and analyses of the concrete structures showed that an appreciable deterioration affected the plinths and piers closer to the internal courtyard of the building, where an absorbing well was active in the first 15 years from building construction. From the analytical data, it was possible to clearly recognise a sulfate attack, induced by sulphuric acid yielded by microorganism metabolism of sewage. The chemical degradation was accompanied by a dramatic strength loss. Large amounts of gypsum crystals grew mainly at the transition zone, inducing a complete debonding between the cement paste and quartz aggregates.

Therefore, in this case, ettringite expansion phenomenon alone was inadequate to explain the strong deterioration of the concrete, and the loss of strength and adhesion of the cement paste was primarily ascribed to the decalcification process of C–S–H, which is responsible for the binding capacity of the cement paste.

The loss of strength and adhesion of the cement matrix related to the decalcification of the calcium silicate hydrate caused by the presence of sulfate has been found in the deterioration of both concrete structures and historical buildings.

A typical "knee" distribution of gypsum in the more affected piers was observed, with the largest amount located at a height of about 1 m. In fact, the sulfate attack progressively decreased in time due to the work stoppage of the well after about 15 years from the building construction; however, the well remained active in keeping wet the building foundations up to today. Multiple dissolution–precipitation steps of gypsum due to water evaporation at an increasing height in the pier can therefore explain the present distribution of gypsum amount.

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