DIAGNOSIS OF CONCRETE STRUCTURES AFFECTED BY ALCALI AGGREGATE REACTION

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Through the study of four pathological cases selected for their instructional value or for the particular way in which the disorders appeared, the different aspects of the diagnosis are explained : General method of diagnosis, typology of the disorders, quantification of microfissuration and gel morphology.
In addition, the results of the study of these specific cases are clarified in terms of : The reaction products/microfissuration relation, the AAR/ettringite relation and the role of Portlandite

INTRODUCTION

This paper describes, through a number of remarkable examples, the diagnosis method developed by the authors, as well as the lessons drawn and the data collected in the case studies dealt with.

These case studies concern structures located in the Paris region, in the North of mainland France and in the French Antilles, particularly St Martin's Island.

Since most of the examples covered are the subject of legal proceedings, the exact location of the sites will not be stated.

The examples have been selected for their instructional value in terms of variation in kinetics of development, the typology of the disorders and the points of general information which can be drawn from them.

The examples given relate to:

- A water reservoir and a residential hotel in the French West Indies, notably because of the intensity and particular speed with which the disorders caused by AAR have materialised.

- A sports facility in the North of France, for the general lessons which this lesson provides with regard to the reaction mechanisms of the Tournaisian limestone.

- A building in the Paris region where the materialisation of AAR in pre-cast balcony elements resulted in a very particular type of disorder.

METHOD OF DIAGNOSIS

In a general manner, the method of diagnosis used aims at:

- identifying the causes and extent of the disorders observed
- estimating their probable development
- defining suitable treatment or remedial solutions.

In most cases, this method involved all or some of the following site or laboratory investigations :

- Detailed visual inspection, survey of the disorders
- Identification of classes of disorders according to their typology
- Selection of areas of investigation representative of the different classes of disorder
- Non-destructive testing on site:
  - . density and opening of cracks, cover to reinforcement, carbonation, ultrasonic testing, etc.
- Taking representative samples, usually by core sampling
- Laboratory testing, including in particular:
  - . reconstituting the composition of the concretes: by chemical analysis - X.R.D. - petrography, aiming to identify the nature of the aggregates and cement used, the reactivity of the aggregates, the alkali content, cement proportions, water content, physical characteristics such as density, porosity, permeability, etc.

- Identifying pathogenic compounds by examination with optical microscope and scanning electronic microscope, on thin slivers, polished sections, fracture surfaces and X-ray diffraction.

- Quantifying the degree of microfissuration by optical microscope examination on polished sections after treatment with a fluorescent resin.

- Estimating residual mechanical strengths by means of mechanical tests on core samples.

- Estimating residual expansion by expansion tests on core samples at 38 degrees C and 100% relative humidity.

CASE STUDY - TYPOLOGY OF DISORDERS

CASE N° 1

Structures in the North of France

At the present time, over one hundred structures in the North of France are known to be affected by AAR. In most of these cases, the aggregates used in the concrete are hard Tournaisian or Givetian limestones.

Most of the structures currently known to be affected are bridges.

The case studied here after is an athletism stradium qbuilt in 1975.

Most of the concretes were made using.

using Tournaisian limestones, and others
using porphyry aggregates.

AAR gels have been identified in most of the elements of the structure, to different degrees.

The disorders manifest themselves by generalised macro cracking (balustrades, terraces, pylon foundations, corbels, mast roofing supports). Oriented cracking of the masts which consist of pre-cast, pre-stressed voussoirs, has also been observed and its relationship with AAR is currently being investigated.
See photographs n° 1 to 4 - annex 1.

The more exposed parts are the most severely affected by AAR.

Structures in the French West Indies

In the French West Indies, taking into account the climatic conditions and the particular reactivity of the aggregates, the phenomena are characterised by their rapid appearance.

CASE N° 2

5000 m3 potable water reservoir

This water reservoir was built in 1986. In 1987, initial manifestations of disorder were observed in the form of spalling cone "pop-outs".

At present, the reservoir is riddled with pop-outs, and generalised macro cracking has developed. In addition, plane delamination cracking has been observed. The structure's safety no longer being assured, rebuilding is now in process some six years after construction.

It should be noted, in this instance, that AAR and corrosion of the reinforcements have acted as synergic pathogenic phenomena. In fact, the concrete contains a very large proportion of chlorides (up to 1% of the weight of the cement) and corrosion to the reinforcements is currently becoming generalised. The cracks resulting from AAR form easy access routes for the water and oxygen needed for the corrosion phenomenon to develop, and vice versa.

The disorders are generalised, with greater intensity in areas where the waterproofing is breached.

See photographs Nos 5 and 6 annex 1.

CASE N° 3
Residential hotel

A further example of rapid reactivity without any synergetic effect due to chlorides is provided by a residential hotel completed in December 1988. In July 1989, a large number of pop-outs were observed, and the frequency with which they appeared was later amplified when macro cross-cracking and major structural disorders also appeared.

At the present time, approximately 70% of the rooms are affected by the phenomenon of more or less intense pop-out formation, appearing mostly in areas particularly exposed to humidity.

See photographs Nos. 7 - 8 - annex 1

CASE N° 4
Pre-cast balconies in the Paris region

The example below is quoted for the particular nature of the disorders occurring.

This AAR phenomenon, affecting the pre-cast, unwaterproofed, balconies of this building in the Paris region is, in fact, causing hogging to the balconies which, at present, are all countersloping.

This is explained by the fact that expansion of the concrete takes place more freely on the underside of the balcony slab (unreinforced part), causing hogging to the balconies. See figure n° 1.

In addition, the intensity of the hogging is directly related to exposure to bad weather.

The balconies on the higher floors, which are the most exposed, exhibit the greatest counterslope.

On the fifth floor, the balcony located to the right of a gable wall which protects it from direct rainfall exhibits less hogging than its more exposed neighbour.

See photographs Nos. 9 - 10 - annex 1

COMPOSITION OF CONCRETES - CHARACTERISATION OF AGGREGATES

Composition of concretes

The reconstituted compositions and principal characteristics of the concretes are given below:

	Type of concrete	Type of cement	Cement content (kg/m3)	Apparent density (kg/m3)	Alkali content kg/m3 Na_2O eq	Aggregates
CASE No.1 Sports facility,	Reinforced	OPC	350-400	2220-2320	2.5-3.2	Tournaisian limestone
North of France	Pre-cast voussoirs	OPC	320-420	2224-2310	1.7-4.0	Tournaisian limestone - porphyry
	Pre-cast balustrades	OPC	390	2170-2250	2.9-5.3	Tournaisian limestone
CASE No. 2 Reservoir, W. Indies	Reinforced	OPC	300-400	1890-2110	2.7-4.1	Metamorphic lava
CASE No. 3 Hotel, W. Indies	Reinforced	OPC	315-380	2030-2150	2.5-3,4	Metamorphic lava
CASE No. 4 Balconies, Paris region	Pre-cast by stoving	OPC	350-400	2190-2200	n/k	Quartzite

Characterisation of aggregates

Identification of reactive materials

The nature of the aggregates and identification of the materials which had reacted were determined by petrographic examination of thin slivers of concrete, with observation by scanning electron microscope where appropriate.

CASE N° 1 - Sports facility in the North of France

Two types of rock used as aggregates were identified. These were, firstly, a porphyritic rock of Belgian origin and, secondly, Tournaisian calcareous marl.

1. The porphyritic rocks

These are highly weathered eruptive rocks with a matrix composed of a large proportion of volcanic glass with a large quantity of bipyramid quartz crystals exhibiting advanced disintegration disseminated throughout.

These rocks are classified in the family of paleo-volcanic andesites.

2. Calcareous marls

These are composed of bioclastic and micritic carbonates. The matrix of these carbonates contains many metallic oxides, beaches of clay and significant lattices of microcrystallised silica.

This silica was revealed by a superficial acid attack (HCl 0.3 N for 1 minute) on polished sections of different samples.

Examination of these sections by scanning electron microscope revealed the extent of these lattices of silica. They consist of interconnected grids of fibrous or cryptocrystalline silica with a lot of partly disintegrated bipyramid quartzes, a lot of framboidal pyrites, pockets of clay, and metallic oxides, in the grid.

The vitreous and siliceous phases of these aggregates are mineral materials which have reacted within the concretes.
See photographs n° 1 - 3-4-5 - Annex 2.

A reactivity test on pre-polished aggregates, immersing them for three days in a lime-saturated alkaline solution heated to 80 degrees C, was also carried out.

The samples examined by scanning electron microscope all exhibit areas of attack, with development of reaction products.

These products are located in the vitreous paste of the porphyritic rocks with very variable facies of AAR gel.

The reactions on the limestones are more vigorous and more widespread, and are a function of the extent of the siliceous lattice. The gel facies are also very varied.

See photograph n° 2 - annex 2.

CASES N° 2 AND 3

In both cases, the aggregates came from St Martin's Island which is geologically constituted of a volcanic and sedimentary series intersected by a plutonic complex, and has been affected by widespread metamorphic phenomena.

The aggregates used in the concretes are very complex, highly metamorphic rocks. Mineralogical identification by petrographic examination revealed that they contain three types of reactive rock:

- Basic rocks of the basalt family and ancient metamorphic basaltic lava. These rocks contain a significant vitreous phase.

- Greenish-coloured rocks, some stratified, strongly metamorphic. These rocks are very finely crystallised and highly weathered.

  They are essentially siliceous in nature. The silica is fibrous or cryptocrystalline, and frequently contains small bipyramid quartzes and some opal.

- Whitish-grey rocks with a carbonated matrix, containing many lattices of fibrous or cryptocrystalline silica.

Petrographic examination of the concrete, and reactivity tests consisting of immersing a sample of the aggregates in a standard lime-saturated alkaline solution, heated to 60 degrees C, for three days, enabled us to establish the high reactivity of the suspect materials revealed.

EXPANSIVE NATURE OF REACTION PRODUCTS AAR/MICROFISSURATION RELATIONSHIP

The following can be observed in the examples presented:

- a direct reactive aggregate/microfissuration relationship, generally revealed by the presence of radial microfissures emanating from the reactive site.
Photograph n° 6 - annex 2.

- a certain parallel between the degree of cracking and the extent of the reaction products observed by microstructural investigations.

- characteristic facies of crystallised products, agglomerated due to the initially very limited space for their expansion. These facies reveal the expansive nature of the products, resulting inevitably in microfissuration emanating from the reaction site.
Photograph 7 - annex 2.

Both these points are still being appraised in too qualitative a manner even by experienced operators. Propagation of cracks is also highly influenced by the presence of prestressing directions within the concrete.

For these reasons, we have developed a method for appraising cracking at microscopic scale, which is intended to permit quantification of criteria which are all too frequently subjective.

This method consists of revealing, on polished sections, areas of discontinuity such as cracks and cement paste/aggregate interfaces. These phenomena are revealed after impregnation with a resin loaded with an ultra-violet radiation fluorescent marker. The appraisal itself is carried out by counting under a binocular microscope using a random series method.

Each analysis is carried out in equidistant lines, successively implanted on a set of equiangular directions. The parameters obtained by the method are:

- a coefficient of cracking related to the frequency of the phenomena encountered,

- spacial distribution allowing detection of any anisotropies in direct relation with the geometry of the structure.
Photographs 10-11-12 - annex 2.

Application of this method produces encouraging results and already allows the degree of deterioration at a given moment to be defined more objectively, as well as permitting a more rational approach to the study of the AAR/deterioration relation.

Example of microcracking/AAR reaction products relationship case n° 1.

Core sample	AAR	Secondary ettringite	OTHER	(1) CF
M-1-2	A few rare lamellar rosettes in the pores of the black aggregates Potassic gels	Not observed	0.07	
V-4-1	Some porphyric aggregates reacted very strongly, others not at all. Gels to 20 microns at times. Potassic gels, may contain small quantity of sodium.	Not observed	0.17	
V-5-1	Not observed	Not observed	0.20	
A-1-1	All the aggregates reacted, to various degrees. Gels in cracks and pores. Potassic gels.	Large quantities present locally. Located in pores and on surface of particles of siliceous sand.		0.30
V-2-1	Gels on part of the aggregates only. Potassic gels.	Not observed	0.37	
P-2-1	Very intense reactions. Gels very widespread and very thick (occasionally 50 microns). Potassic gels.	Large quantity Located on surface of gels, in pores and where in contact with particles of siliceous sand.	Traces of CSH locally, carbonated at centre of core sample. Complex dissolutions with formation of calcic pockets on surface of gels.	0.76

(1) Coefficient of cracking.

<u>MICROSTRUCTURAL INSPECTIONS</u>

Micro-facies of alkali/aggregate type reaction products

In the examples of structures affected by the alkali/aggregate reactions which we are describing, a remarkable diversity of observed reaction products will be noted: diversity in terms of extent, location, composition, and, above all, the micro-facies of the products. This point is a good indication of the extent of the research required for greater comprehension of these phenomena.
Photographs n° 10 to 11 - annex 2.

Characteristics particular to any one type of aggregate are nevertheless worth noting:
- calcareous aggregates, North of France:

The first silico-calco-alkali formations appear in the micropores of the aggregates as well as at the interface with the cement paste. These are most frequently lamellar rosette-shaped crystallised gels. Amorphous gels are present in the cement paste, probably after migration via the neo-microfissuration. The further they are from the reactive site, the more calcic their nature.
Photograph n° 16 - annex 2.

- porphyric aggregates, North of France:

In certain structures, where they are present in conjunction with the calcareous aggregates described previously and consequently in the same environment in terms of hydrated lime and available alkalis, porphyric aggregates usually result in non-crystalline forms of reaction products.

- metamorphic calco-siliceous aggregates, French Antilles :

The gels are generally uncrystallised but sometimes have very low alkali contents, not detected by X-ray energy selection analysis.

- siliceous aggregates, Paris region:

The reactive forms of fibrous and amorphous cryptocrystalline silica which these contain reacted firmly with the alkalis in the cement. Uncrystallised gels are observed on the botryoidal surface, but they are surmounted by crystallised lamellar potassic products formed during a later stage of the reactions.

These four examples should be accompanied by less frequent characteristics which reveal the complexity of the mechanisms at the origin of these micro-facies:

- this is so in the West Indies example, where the cracking caused by AAR probably allowed the formation of calcite on the actual surface of the smooth gels, by carbonation.

- it is also so in the North of France example, where the most severely affected parts exhibit very thick gels (600 μm) on the surface: extensive calcic pockets, neoformed ettringite with facies comparable to primary ettringite, intense vertical developments with very variable morphology, unreferenced at the present time.

Secondary ettringite and AAR

A large number of structures affected by very advanced AAR have exhibited the simultaneous presence of as yet unexplained expansive secondary ettringite.

Photographs n° 13 to 14 - annex 2.
In some of the examples described, this is probably due to the relation with a sulphatic reaction, linked to the presence of a large quantity of pyrites in the form of framboidal concretions within the aggregates, the secondary ettringite then resulting from oxidation of these concretions, according to DELOYE. This is so in the case of the calco-siliceous aggregates from the North of France described previously.

In the cases described, this phenomenon has, however, also been observed when there is no sulphur in the aggregate, deep within structures affected by AAR. This is so in the case of the siliceous aggregates from the North of France.

The microstructural characteristics of this ettringite are as follows:

- dense superficial deposits at the hydrated cement paste/aggregate interface,

- more localised formations on the actual surface of uncrystallised gels, without any apparent microstructural discontinuity between the gel and the neoformed ettringite,

- fine needles entangled with facies of primary ettringite on gels, occasionally on the micro-crystallised surface, frequently associated with calcic pockets.

Current research should bring about improved knowledge of these phenomena.

Involvement of hydrated lime in the first stages of alkali-aggregate reactions

The role of lime (publications)

Several authors working on alkali-silica reaction mechanisms have demonstrated that the presence of lime is necessary for the formation of ASR gels (DIAMOND, STRUBLE, KILGOUR, CHATTERJI).

There are two schools of thought: according to STEINOUR and POWERS, as well as H. WANG and GILLOT, silico-alkali gels are expansive, whereas silico-calco-alkali gels are not.

Whereas according to CHATTERJI, lime plays a role in the process of diffusion of Na^{+} and Ca^{++} cations within the reactional sites of silica, and he rejects the idea of non-expansive silico-calco-alkali gels. For this author, the presence of lime is necessary if alkalis are to diffuse within the reactive siliceous sites.

- diffusion of a few molecules of silica outside their initial sites. The presence of the lime required for the formation of expansive gels is confirmed by several experiments, such as:

- the role of pozzolanic additives (reducing expansion), reducing the lime content of mortars and concretes (silica fumes, slags, fly-ash) even where the cements are very rich in alkalis,

- the absence of gels when a reactive aggregate is tested by immersion in a standard NaOH solution; whereas there is gel formation when the attack solution is saturated with $Ca(OH)2$.

Furthermore, it has been shown that the potassium silicate which forms during the alkali-silica reaction has a pH of between 11.3 and 12.1.

In this pH band, the lime breaks down, freeing Ca^{++} ions.

Micro-structural studies of the cases presented here, involving concretes hosting AARs, illustrate this type of process well.

The role of lime - Case study

An examination of the different concretes affected by AAR type reactions has highlighted the role of hydrated lime in the formation of reactive products.

Advanced cases of reaction:

Microstructural studies carried out in classic manner in the laboratory always demonstrate the silico-calco-alkaline nature of the products, whether they be crystallised or amorphous in form. The lime contents detected by X-ray energy selection spectometric analysis, using a scanning electron microscope, are always consistent and confirm the involvement of hydrated lime in alkali-aggregate reactions.

Two observations particular to the cases presented here illustrate this phenomenon:

- the very thick gels observed in the North of France usually have vertical developments of complex facies which are more calcic in nature the larger they are.

- in some cases, the formation of gels is observed not actually on the aggregate containing the reactive forms of silica, but in a more delocalised manner. This point is significant in certain structures in the North of France, where the gels form within vacuoles located in the vicinity of the aggregate.

Not very advanced cases of reaction:

Microstructural examination of different types of composition of concrete and of different reactive aggregates highlights the role of lime in the very early stages of the reaction.

In the case of the limestones of the North of France and the metamorphic rocks of the West Indies, the following are observed :

- the characteristic facies of disintegration of the lime present in the automorphous crystals at the interface between the cement paste and the reactive aggregate,

- the thin calcic effusions emanating from these crystals in the course of disintegration. Such effusions are only slightly crackled and fill the micropores of the site, aggregate and paste.

- in certain cases, pockets of calcic formations have re-formed on the actual site of disintegration, indicating some modification of the physico-chemical attack conditions. Photographs n° 15 - 16 - annex 2.

CONCLUSION

The diagnostic method presented not only permits identification of the existence of the alkali-aggregate reaction and the nature of the reactive materials involved, as well as the pathological results visible in the structure, but also provides a quantitative method allowing the cracking density and the observed reaction products to be correlated.

In addition, a study of the cases presented provides information about gel morphology as a function of the types of aggregate and the state of development of the structures, and also contributes to the understanding of the mechanisms of ettringite formation and the role of calcium in the alkali-aggregate reaction.

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A N N E X 1

SITE VIEW - TYPOLOGY OF DESORDERS

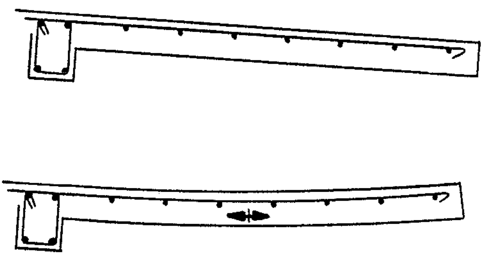
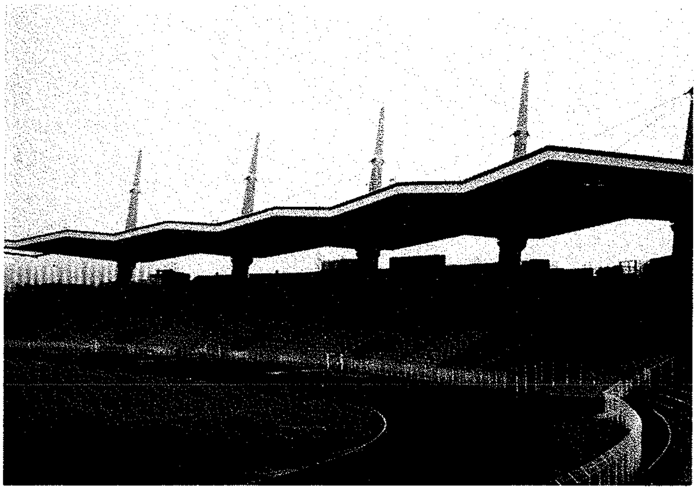
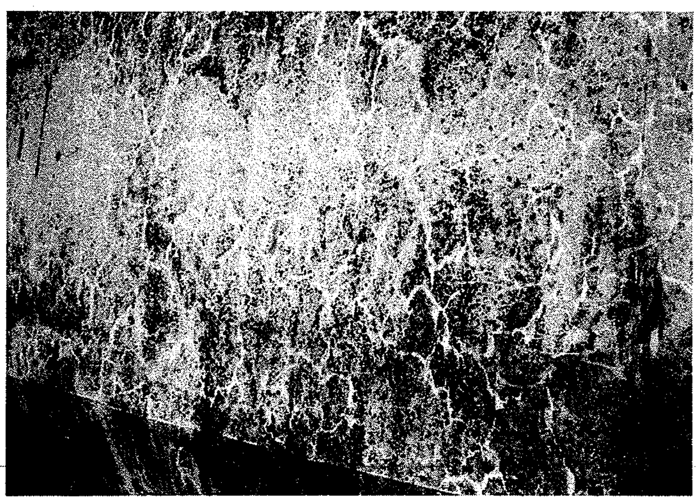


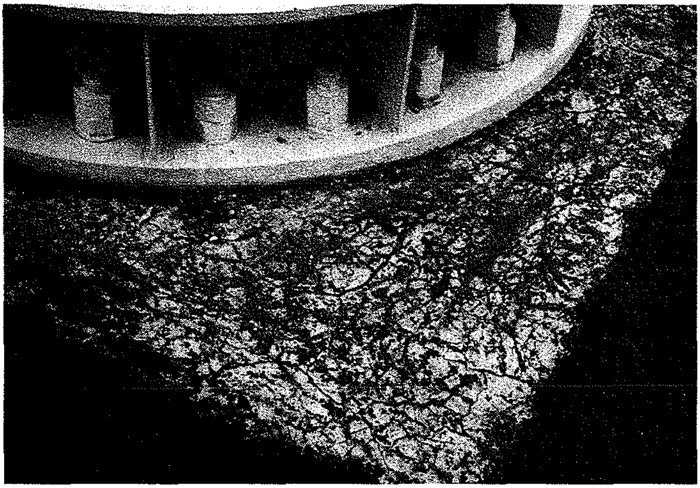
FIGURE 1 -
EXPANSION ON THE UNDERSIDE CAUSING HOGGING TO THE BALCONIES



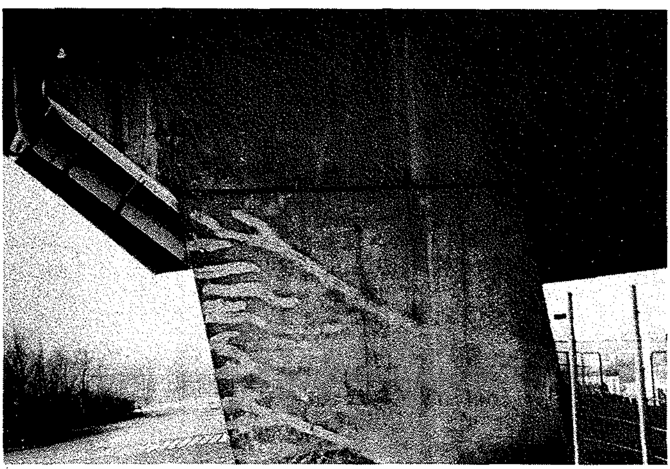
N° 1 - CASE N° 1
Stadium general view



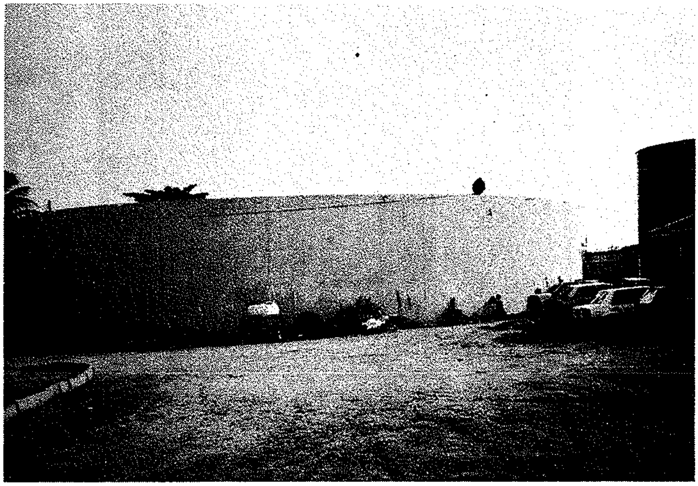
N° 2 - Macrocracking on Breast wall



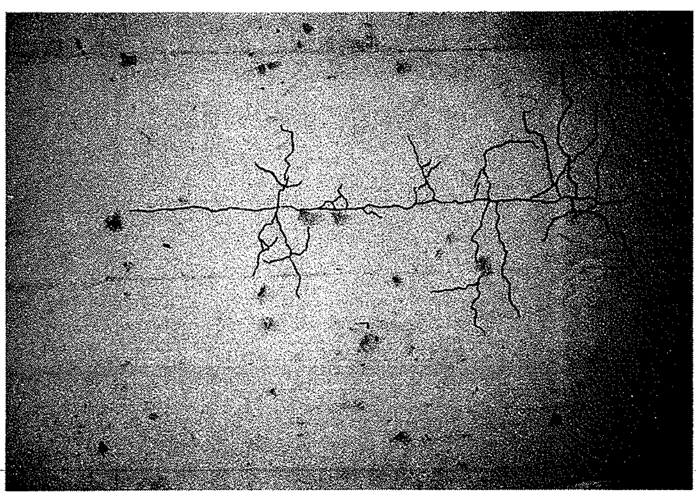
N° 3 - Pylone black foundation



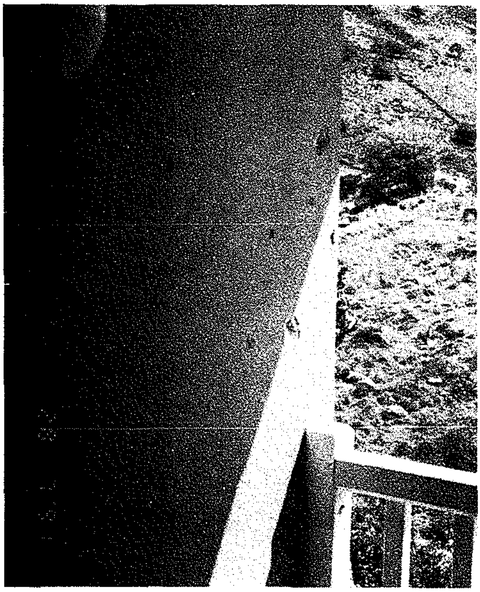
N° 4 - Prestressed columns bases
- Directionnal cracking



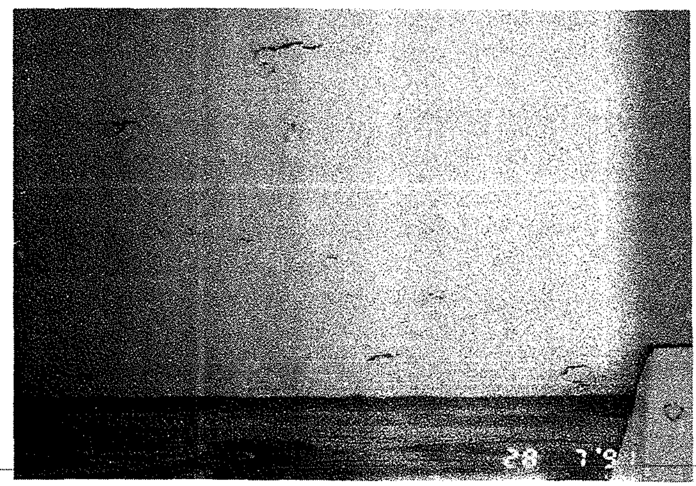
N° 5 - CASE N° 2
Tank General view



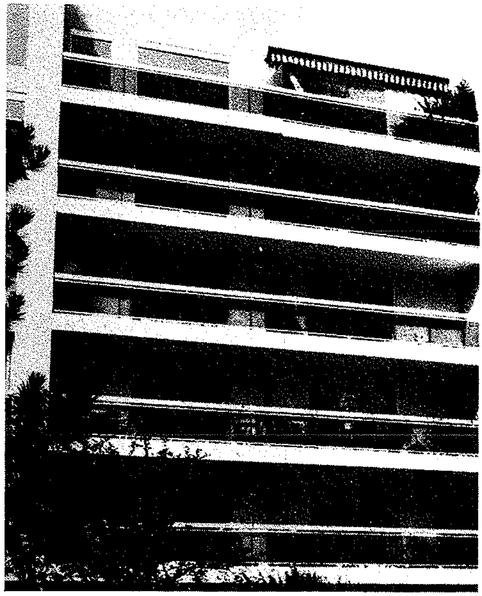
N° 6 - Water tank
- Microcraking and pop out



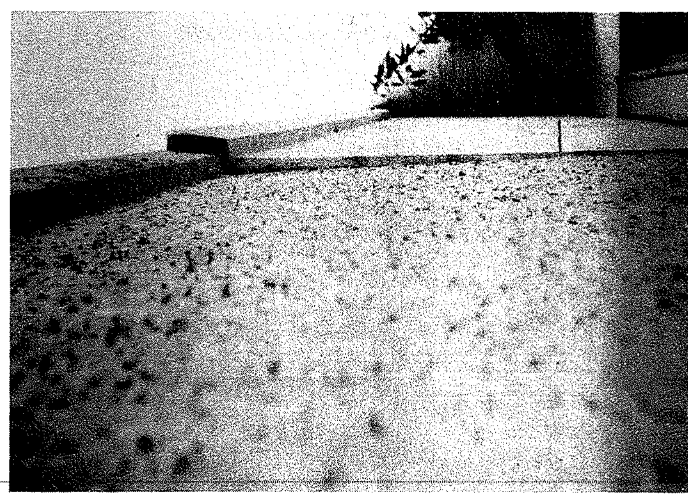
N° 7 - CASE N° 3
- Pop out on loggia wolls



N° 8 - Pop out under concrete landing of stairs



N° 9 - CASE N° 4 - Building general view with visible balcony movement at 3th level



N° 10 - View from 4th level

A N N E X 2

MICROSTRUCTURAL EXAMINATIONS

LIMESTONE AGGREGATE SILICA MATRIX (NHORTH FRANCE CARBONATES)

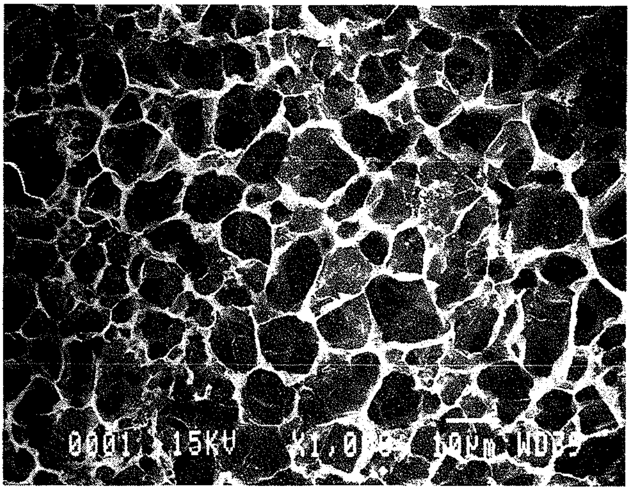


FIG N° 1 : mag. x 1000
Alveolar silica matrix detection after carbonate dissolution

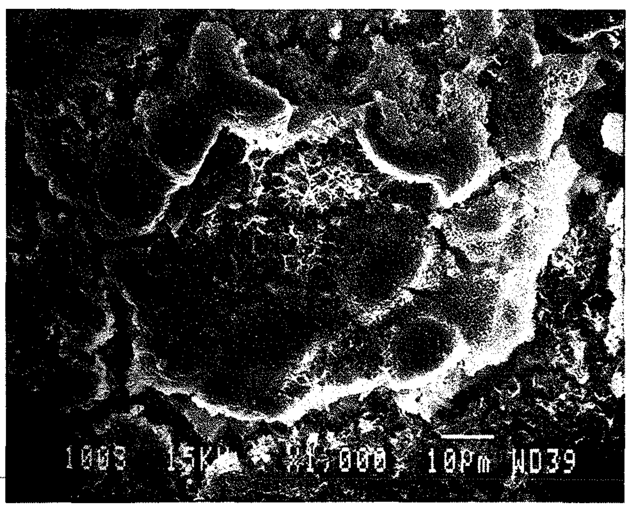


FIG N° 2 : mag. x 1000
Products of the A.S.R. after reactivity CEBTP test

GRAINS OF PYRITE FACIES (NORTH FRANCE CARBONATE)

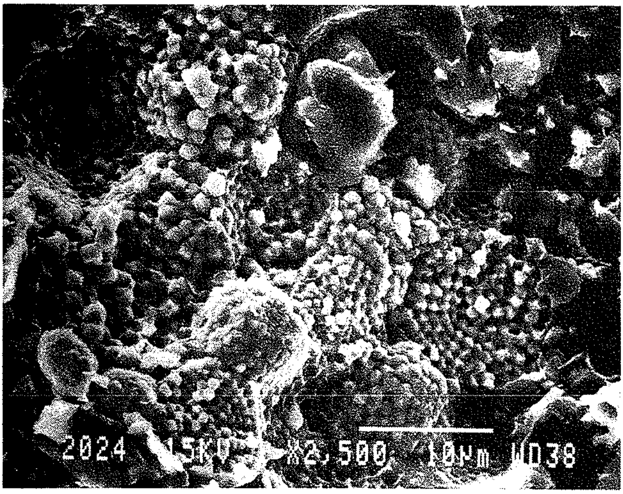


FIG N° 3 : mag. x 2500
Rapsberry pyrites between microsparite crystals

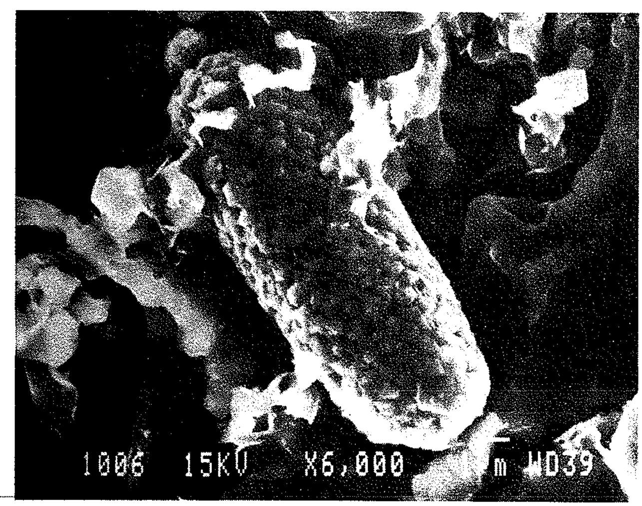


FIG N° 4 : mag. x 6000
"Ear corn" aspect of pyrite

GRAINS OF PYRITE FACIES (NORTH FRANCE CARBONATE)

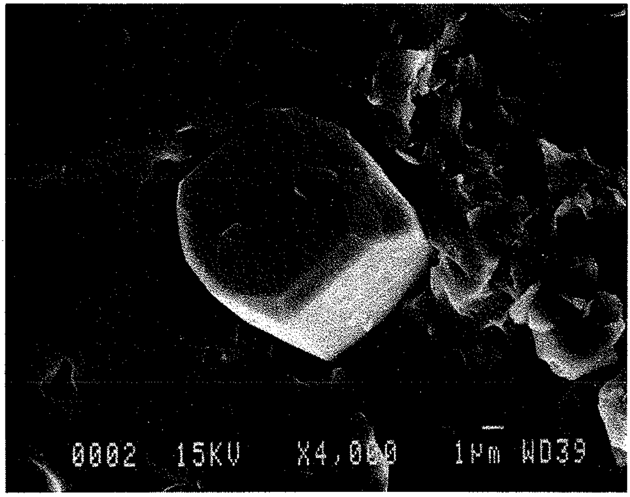


FIG. N° 5 - mag. x 4000
Automorphic crystal of pyrite

S.E.M. MICROGRAPHS OF A.S.R. PRODUCTS

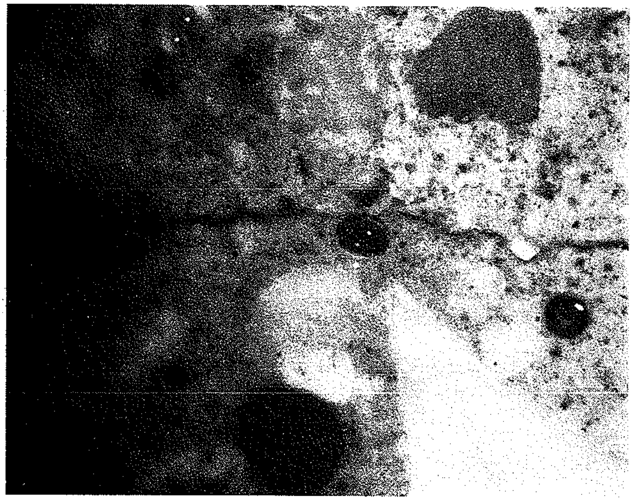


FIG N° 6 : mag. x 16
Microcrack and associated aggregate

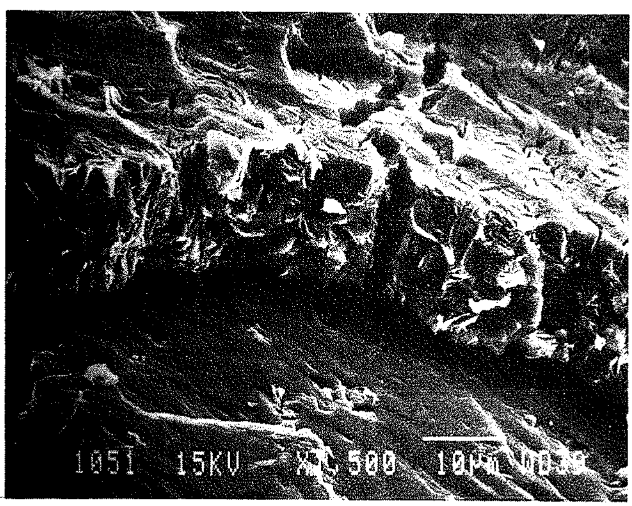


FIG N° 7 : Mag. x 1500
Massive rosette like appearance of A.S.R. product

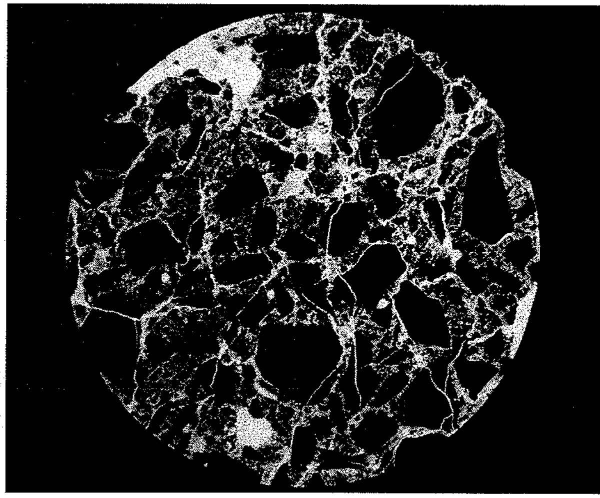


FIG N° 8 : mag. x 1
Microcracks view at the surface layer of a concrete cylinder

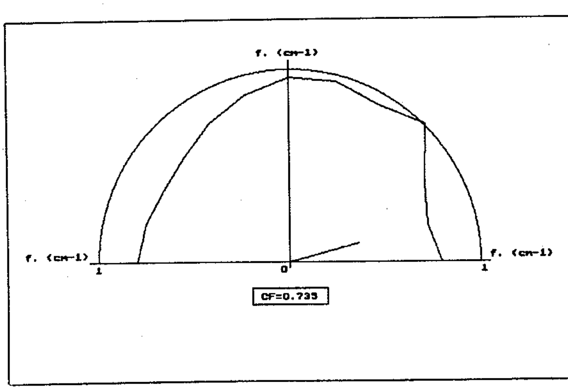


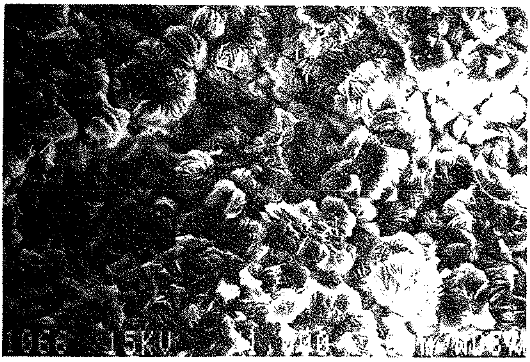
FIG N° 9
Microcracks polar curve of fig. n° 8

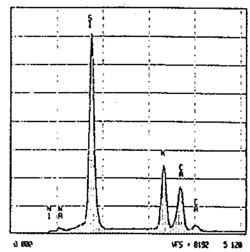
S.E.M. MICROGRAPHS OF A.S.R. PRODUCTS

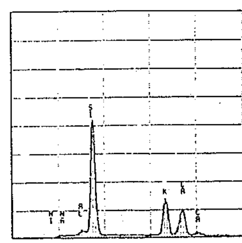
FIG N° 10 : mag. x 3000
Primary rosette - like crystals into aggregate microcrack

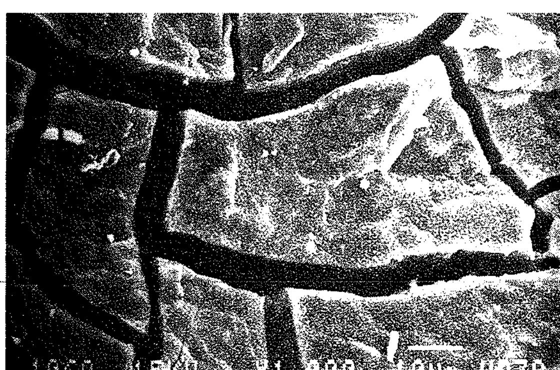
FIG N° 11 : mag. x 1500
Secondary lamellar - like crystals onto botryoïdal gel

MICROSTRUCTURES OF A.S.R. PRODUCTS AND SEMI-QUANTITATIVE EDS ANALYSIS (Fig. n° 12)









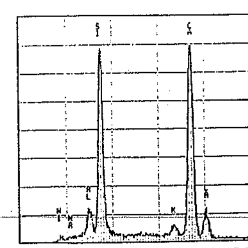


FIG N° 13 : mag. x 1300
Massive ettringite in the paste aggregate interface

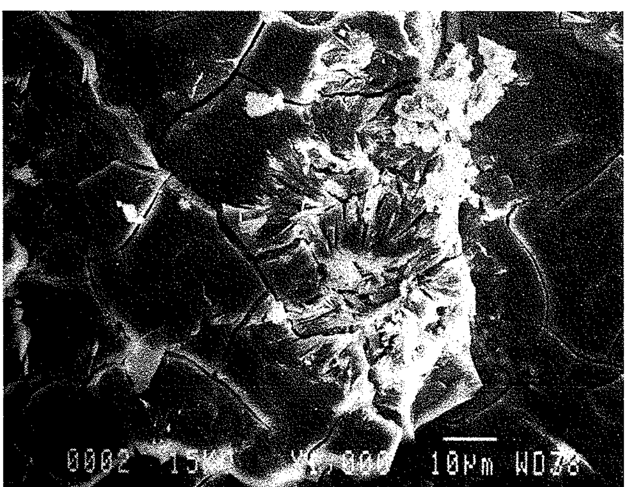


FIG N° 14 : mag. x 1000 - Continuous micro-structure between A.S.R. products and secondary ettringite

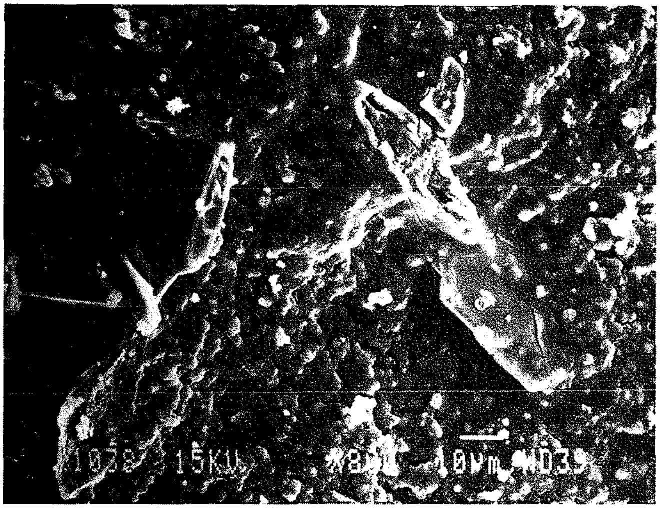


FIG N° 15 : mag. x 800 Dissolution of automorphic lime crystals and associated calcic effusions

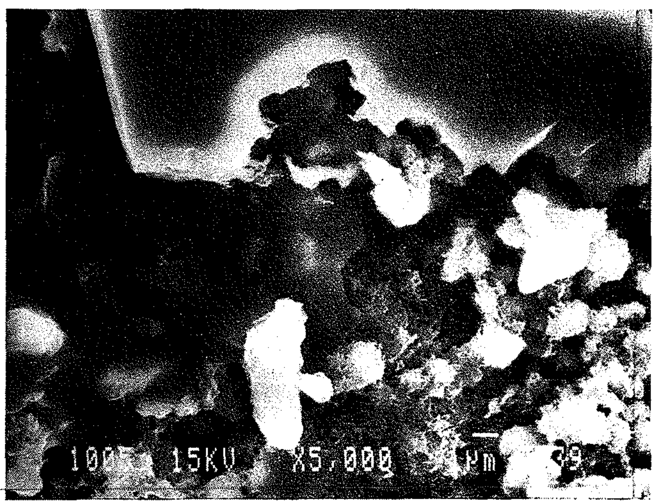


FIG N° 16 : mag. x 5000 - Charasteristic lime dissolution figure