

**DIAGNOSIS OF ALKALI-AGGREGATE REACTION  
AND SULPHATE REACTION IN FRENCH STRUCTURES**

**C. LARIVE, N. LOUARN**

Laboratoire Central des Ponts et Chaussées, Paris, France.

A score of bridges exhibiting symptoms of binder-aggregate reaction have been surveyed by the Laboratoire Central des Ponts et Chaussées. The scanning electron microscope (SEM) equipped with an energy dispersive probe was used to identify, locate and qualitatively analyze the degradation products. The results so obtained plus information about the building materials and the age and type of structures have been grouped in a data base. This was processed to yield a proposal for the classification of alkali-aggregate reaction and sulphate activity products, found together in almost all of the samples. It revealed locations favoured by, but not characteristic of, the various morphologies. The observations by the SEM and the qualitative analyses support the hypothesis of an evolution of alkali-aggregate reaction gels into crystallized products. For both reactions, the respective roles of the various constituents of the concrete are estimated. The heterogeneity of the phenomena is emphasized.

**1. INTRODUCTION**

France first faced the problem of the alkali-aggregate reaction in 1976, during the investigation of the swelling of the Chambon dam (Cornicille (1)). It was only ten years later that damage of this same origin was found in bridges. Expert appraisals were then begun on structures exhibiting damage attributable to a binder-aggregate reaction (alkali-aggregate reaction or sulphate reaction). Since then, three of them have had to be demolished.

The apparent damage regarded as most characteristic of such degradation includes the following (Godart (2)) :

- **cracking** : map-cracking ; oriented cracks, in the case of structures that are prestressed or subjected to anisotropic mechanical stresses ; relative displacement of the crack edges.
- **abnormal strains** : global swelling of all or part of the structure, residual strains.
- **ancillary phenomena** : pop-outs, ochre colouring, exudates.

These symptoms are not enough to establish a diagnostic. To yield a reliable diagnosis, analysis should move to the scale of the material ingredients.

One of the many approaches taken to achieve a better understanding of these phenomena has consisted of surveying doubtful structures. During the last four years, nineteen bridges have been studied in this way by the Laboratoire Central des Ponts et Chaussées (LCPC). Their concretes have been subjected to various investigations to determine the origin of the degradations. The purpose of this paper is to present the results of studies of the microstructure, of the qualitative elementary chemical composition and of the localization of the reaction products. The techniques used for this are scanning electron microscopy and energy-dispersive X-ray analysis. Before commenting on the obtained information, we shall briefly describe the method used to conduct a complete expert appraisal, then present the structures on which the researches were carried out, and finally consider the correlations between appearance, location, and composition of products on the one hand, and building materials, age, and type of structure on the other hand.

## 2. STEPS IN A COMPLETE EXPERT APPRAISAL AT THE LCPC

### 2.1. Sampling

Several core drillings are generally taken from the structures at different depths (from 30 cm to 1 m). Exceptionally, in one case, sampling was done at the surface (from 2 to 3 cm in depth). Most of the cores are taken in the damaged zones, some in sound zones to provide a comparison. The cores are kept in sealed bags while awaiting processing.

### 2.2. Laboratory investigations

These had the following objectives :

- Identification of the mineral species :
  - by petrographic analysis,
  - by X-ray diffractometry,
  - by differential thermal analysis.
- Quantification of chemical constituents :
  - by centesimal chemical analysis,
  - by thermogravimetric analysis.
- Study of microstructure :
  - by scanning electron microscopy.
- Qualitative composition of products :
  - by energy dispersive probe.

The results given in this paper are limited to the study of the microtextures of degradation products and their qualitative chemical composition. We chose to work on freshly broken concrete in order to preserve the appearance and location of deleterious products. Prior observation under binocular loupe served to identify the most visible signs : rims around aggregates, deposits in pores, paste and on the fractures of calcareous aggregates. These zones are selected for further observations by the scanning electron microscope (SEM). Their microstructure is compared with those of sound zones.

### 2.3. Results of an expert appraisal

Preparation by fracture makes analysis delicate (surface irregularities) and can lead to overestimating the degradation (preferential failure of the concrete along planes of greater brittleness), but it has the advantage of allowing early detection of damage.

The information accumulated in the course of these investigations leads to two types of interpretation, one qualitative, the other quantitative. The former concerns the type of minerals involved, the morphology of the products formed, their location, their occurrence frequency and their qualitative composition. The latter uses the "Mineral" software (Deloye (3)) to convert the results of the chemical analysis and thermogravimetry into the quantitative mineralogical composition of the concrete. The latest version can quantify the excess of soluble silica due to an alkali-aggregate reaction and the excess of sulphates due to a sulphate reaction (Deloye and Divet (4)).

## 3. CHARACTERIZATION OF THE STRUCTURES CONCERNED BY THE STUDY

### 3.1. Age and location

The nineteen bridges surveyed were built between 1936 and 1981 : two before 1950, eleven in the 1970s, and six after 1980. Twelve of them are in the Nord-Pas-de-Calais region, four in the Paris area, one in Bretagne, one in the Pays de Loire, and one in Auvergne. Only four concrete bridges in the Nord-Pas-de-Calais region are prestressed ; all the others are reinforced.

### 3.2. Building materials

The concrete gravel of the sixteen bridges in the Nord-Pas-de-Calais region and the Paris area is limestone, sometimes dolomitic, rich in diffuse silica. It comes from both the Tournai and the Avesnes area. It also contains pyrites and clays. The other three bridges contain siliceous gravel (quartzite, granite, gneiss). All these types of gravel have been recognized as potentially reactive. The sands used are of various origins. Only one is classified non-reactive.

In two structures, according to mineralogical calculations performed on already damaged concretes, the Na<sub>2</sub>O equivalent content of the cements is slightly less than 0.6%. It is between 0.6 and 0.8% in nine of them, between 0.8 and 1% in five others, and between 1 and 1.22% in the last three. Measurements of alkalis in kg/m<sup>3</sup> of concrete, by attack with nitric acid diluted to 1/50, may vary within a given structure, in different cores. The measured values are 3.07 and 3.49 kg/m<sup>3</sup> in two samples, between 3.5 and 5 in fifteen, and between 5 and 6.59 in four others.

### 3.3. Location of damage

Damages were found in various parts of the structures : slabs, beams, capping beams, piers, abutments, abutment piers and retaining walls. They are found primarily in very wet zones. This well known phenomenon is mentioned by many authors, including Baronio and Berra (5), Blight (6), Chatterji (7), Hobbs (8), Ludwig (9) and Regourd (10).

## 4. RESULTS

A data base, describing the structures (age, location, type and building materials) and their degradation products (microtexture, dimensions, location and composition), was constituted to facilitate analysis of the information gathered in the course of a four years survey (1987-1991). Our work (covering more than 400 microscopic preparations) confirms the assumption of binder-aggregate reactions and reveals the characteristic products of an alkali-aggregate reaction and of sulphate activity. In the great majority of cases, these two reactions are detected simultaneously, with the exception of two structures in which each of them was found separately.

### 4.1. Classification of reaction products

The many reaction products, especially those of the alkali-aggregate reaction, have often been described in the literature ((5), Bérubé and Fournier (11), Carse and Dux (12), Dron (13), Larive (14), Oberholster (15), Ohama et al. (16), Regourd and Hornain (17), Samuel et al. (18), Shayan and Quick (19) and Thaulow et al. (20)).

We have deliberately grouped the various textures observed into a small number of categories. Some are difficult to include in this classification, but their low occurrence frequency means that an additional class is not justified. A few photographs are grouped at the end of this paper.

**4.1.1. The alkali-aggregate reaction.** The products resulting from an alkali-aggregate reaction have extremely varied appearances. We propose to divide them into three classes : amorphous, semi-organized, and crystallized. Reference is made to amorphous products or "gels" when there is no resolution at x5000 magnification. The so-called crystallized products exhibit a geometrical motif under the SEM. We did not perform any X-ray diffraction studies of the products observed in the concretes. But, such a study has been recently undertaken at the LCPC on products synthesized in the laboratory from opal and seems to confirm the amorphous character of the "gels" and the crystallinity of the so-called crystallized products (Dron). We have qualified as "semi-organized" those products in which :

- amorphous and crystallized phases were present simultaneously (polymorphous products),
- we were not absolutely certain as to the crystallinity (botryoidal products),
- the texture was similar to that of a precipitate (microgranular products).

All of the percentages given in this paragraph are calculated with respect to the total number of alkali-aggregate reaction products. Within the three groups, representing 50% of cases for the first and 25% for each of the others, the various forms encountered are the following :

- "**amorphous**" products : at x5000 magnification, their cross-section still has a gelatinous appearance. They are divided into two types :
  - *smooth gels* (42%) : they have an even surface and may consist of one or several layers of variable thickness (between 1 and 14  $\mu\text{m}$ , 5  $\mu\text{m}$  on the average).
  - *bump-shaped gels* (8%) : they have a roughened surface and their total thickness is generally not more than ten micrometres, but may in exceptional cases reach 70  $\mu\text{m}$ .

These amorphous products, very rich in water, exhibit under the scanning electron microscope a crazed appearance caused by their desiccation (Baronio (21), Deloye et al. (22)).

- **semi-organized products** :
  - *polymorphous products* (13%) : these are in large part amorphous, with small crystals (less than 10  $\mu\text{m}$ ) of varied facies, scattered on the surface : lamellae, clusters, bunchs, clumps, needles.
  - *botryoidal products* (3%) : these consist of spheres (diameter less than 10  $\mu\text{m}$ ) that it is difficult to resolve even at x5000 magnification.
  - *microgranular products* (9%) : these consist of crystallites and most often develop on a layer of amorphous product. They can be seen clearly only at approximately x3000 magnification or more.
- **crystallized products** :
  - *lamellar crystals* (7%) : individualized lamellae (5  $\mu\text{m}$  on average).
  - *rosette-like crystals* (16%) : groupings of lamellae (mean diameter 10  $\mu\text{m}$ , range 5 to 30  $\mu\text{m}$ ).
  - *acicular crystals* (2%) : fine, short needles (less than 10  $\mu\text{m}$ ).

**4.1.2. The sulphate reaction.** This is always identified by the presence of so-called "secondary" ettringite, as opposed to the primary ettringite that forms in the first stages of hydration of the cement (Dron and Brivot (23)). This ettringite constitutes nearly 50% of the degradation products encountered in our study. It can take different forms, which we have grouped into five classes. The percentages given are calculated with respect to the total number of cases of secondary ettringite.

- *Free ettringite* (20%) : this consists of clearly individualized fine needles, highly variable in length (from 7 to 100  $\mu\text{m}$ , mean 32  $\mu\text{m}$ ).
- *Ettringite in packets* (30%) : the needles (from 3 to 40  $\mu\text{m}$  long, mean 18  $\mu\text{m}$ ) are shorter than those of the free ettringite and are grouped in packets having no favoured orientation.
- *Oriented ettringite* (9%) : the needles are short and individualized (4 to 30  $\mu\text{m}$  long, mean 13  $\mu\text{m}$ ). They are perpendicular or parallel to the surfaces on which they are located.
- *Compressed ettringite* (35%) : the needles are welded together and form thin layers about ten micrometres thick.
- *Compact ettringite* (6%) : the notion of needles disappears and only the elementary analysis can distinguish this form of ettringite from an alkali-aggregate reaction gel. It is less than 10  $\mu\text{m}$  thick.

**Remark:** in a few cases (8 out of 180), elementary analysis using the EDAX probe reveals the simultaneous presence of thaumasite and ettringite.

**4.1.3. Coexistence of the two reactions.** The heterogeneity of the degradations is apparent on all scales :

- On a given microscopic preparation, one or several microtextures may be found. Alkali-aggregate reaction gel and ettringite may also be superposed.
- In some cores, one type of reaction may predominate ; in others, the products described are more uniformly distributed.
- In a given structure, some zones may be perfectly sound, while others are affected by one or by both reactions.

#### 4.2. Location of products as a fonction of their microtexture

A minimum aggregate size of 100 micrometres has been noted as a threshold below which very few deleterious products are found. They tend to occur on aggregates, of two quite distinct sizes, of the order of millimetres or centimetres.

The tables below give, for each microtexture, the frequency of the various locations observed : the cement paste, the bubbles in it, the paste-aggregate interface and cracks in calcareous aggregates.

##### 4.2.1. The alkali-aggregate reaction

TABLE 1 - Locations of alkali-aggregate reaction products (number of cases).

AAR products	paste	bubbles	interfaces	cracks	total
smooth gel	23	2	41	9	75
bump-shaped gel	1	4	8	3	16
botryoidal product	1	1	3	0	5
polymorphous product	3	1	13	6	23
microgranular product	2	8	1	6	17
lamellar crystals	1	1	6	5	13
rosette-like crystals	2	4	7	18	31
acicular crystals	0	0	3	1	4
<b>total</b>	<b>33</b>	<b>21</b>	<b>82</b>	<b>48</b>	<b>184</b>

The amorphous products (smooth and bump-shaped gels) occur primarily at the paste-aggregate interface (49/91) and in the paste (24/91). The majority of crystallized products occur in the cracks of calcareous aggregates (24/48), but they are also found at the paste-aggregate interface (16/48). As for semi-organized products, they are found at the interface (17/45), in cracks (12/45), in bubbles (10/45), and in the paste (6/45).

Very often, at the paste-aggregate interface, there is a transition (within a few hundred micrometres) from a smooth gel, on the paste side, to a bump-shaped gel, then to a few crystals emerging from this amorphous product and finally to clearly individualized crystals, touching the aggregate (11). If the aggregate is foliated or cracked, then there are crystals in its fracture planes (Le Roux and Cadot (24)). Very rarely, the configuration is inverted (crystals touching the paste and smooth gel in a cracked calcareous aggregate). These observations suggest the hypothesis of an amorphous-crystalline evolution. This hypothesis has already been mentioned by Diamond (25) and Shayan and Quick (19).

##### 4.2.2. The sulphate reaction

TABLE 2 - Locations of secondary ettringite (number of cases).

ettringite	paste	bubbles	interfaces	cracks	total
free	11	12	12	0	35
in packets	17	9	30	0	56
oriented	3	2	7	3	15
compressed	7	3	53	1	64
compact	1	2	7	0	10
<b>total</b>	<b>39</b>	<b>28</b>	<b>109</b>	<b>4</b>	<b>180</b>

Table 2 shows that the two most common forms are compressed ettringite and ettringite in packets, located primarily at the paste-aggregate interface. The former differs from the latter in that it forms a veneer covering the aggregate. Then comes free ettringite, distributed between the paste, the bubbles, and the interfaces, but totally absent from the cracks in the aggregates.

The ettringite adapts its crystallization to the available space : the presence of free ettringite at the paste-aggregate interface reveals a pre-existing separation.

For these two reactions, the favoured location of the deleterious products is the paste-aggregate interface : this is the case of 44% of the alkali-aggregate reaction products and 60% of the secondary ettringite. Cracks in calcareous aggregates are also a major site for alkali-aggregate reaction products, but only exceptionally contain secondary ettringite. For both reactions, in the same proportions, the products are more common in the paste than in the bubbles.

Thus, the location of the products is not characteristic of their microtexture (11).

#### 4.3. Composition of products as a function of their microtexture

The SEM is used to observe the various morphologies present, while the energy dispersive probe gives their qualitative elementary analysis. We have worked only on the composition of alkali-aggregate reaction products, since the composition of ettringite is in principle known. In practice, its elementary qualitative analysis sometimes shows a few variations, most often due to the simultaneous presence of thaumasite.

We examined the silicon, calcium and potassium contents, together with the "silicon/calcium" ratio, which may be regarded as a characteristic of the product (Perruchot, (26)). Sodium was rarely detected by the probe : French cements contain very little and the probe is not very sensitive to this element. Aluminium is found only exceptionally. The values indicated below are calculated from the relative heights (H) of the peaks of the X-ray transmission spectrum (on a scale from 0 to 10).

The better crystallized the alkali-aggregate reaction products, the richer in potassium they are : the mean peak height values range from 2.1 for smooth gels to 3.7 for rosette-like and 4 for lamellar crystals.

Our breakdown of alkali-aggregate reaction products into three classes is confirmed by results concerning the  $H_{Si}/H_{Ca}$  ratio : its value for amorphous products - smooth gels, bump-shaped gels - is 0.8 and 1.2, respectively ; it is 1.1, 1.4, and 1.6 for semi-organized products - botryoidal, microgranular and polymorphous - and finally 2.2 and 3.7 for crystallized products - rosette-like and lamellar crystals. The  $H_{Si}/H_{Ca}$  ratio increases with the crystallographic organization of the reaction products.

This variation is due both to the increase in silicon content and to the reduction in calcium content : calcium predominates in 77% of the smooth gels ( $H_{Si}/H_{Ca} < 1$ ), whereas the crystals have a substantially higher silicon content ( $H_{Si}/H_{Ca} \geq 1$  in 86% of them). However, the value of the ratio can reach 2.5 in some smooth gels and be as small as 0.4 in some crystals.

While, on the whole, the results are significant, the variations of this ratio would be of interest for additional studies on laboratory made concretes. This would allow to eliminate the influence of the building materials, of the concrete formula and of its environment. The only non constant parameter would be the microtexture of the alkali-aggregate reaction products.

**4.4. Influence of age, materials and type of structure**

We looked for a relation between the age of the bridges - built from 1936 to 1981 - and the observed degradations. The structures, whether recent or old, contain all forms of reaction products, and their occurrence frequency does not vary significantly. Whatever their age, the quantity of amorphous and semi-organised products is clearly greater than that of crystals. This result is reflected globally in the fact that only 25% of the alkali-aggregate reaction products are properly crystallized.

The sulphate reaction is significantly less advanced in the structures built since 1980. This difference cannot be ascribed to the aggregates, which are identical in several structures of different ages. It does not imply that the reaction is less active but that it may take more than ten years to produce a lot of secondary ettringite. It would be interesting to perform further surveys in a few years so as to compare the structures at the same age.

We also looked for possible differences in the degradation products of reinforced and prestressed concretes : their composition is similar but their locations differ. While the occurrence frequencies are similar in the cement paste and at the paste-aggregate interface, they are clearly different in bubbles and cracks, as shown by table 3. Reaction products are more common in bubbles in prestressed concretes and in cracks in reinforced concretes.

**TABLE 3 - Influence of type of concrete on location of alkali-aggregate reaction and sulphate reaction products (% of products in each type of concrete)**

location	reinforced concrete	prestressed concrete
cement paste	21	16
bubbles	10	21
interfaces	52	56
cracks	17	7

Sixteen of the nineteen structures studied contain calcareous gravels from the Tournai and Avesnes areas. These gravels, rich in diffuse silica, turn out to be especially reactive. Many other bridges built with these limestones are also starting to show alarming signs. The last three structures examined contain siliceous gravels. There is no difference in the appearance, composition or location of the deleterious products. However, the large predominance of limestone makes a valid comparison difficult.

The share of responsibility ascribable to the sands remains undetermined. In most cases, observation by the SEM reveals extensive corrosion of their surface and, sometimes, veneers of silica, amorphous or even crystallized into tridymite or low-temperature cristobalite (Le Roux (27)). The sands manifestly contribute to the degradations, but, so far, at the LCPC, we have not surveyed any structure in which reactivity of the sand alone caused damage, whereas we have found a case of non-reactive sand and reactive gravel.

Zones (from 100 µm to 3 mm) where the EDAX probe detects only iron are found in the paste, near the calcareous aggregates. It also contains illites (approximately 100 µm), the role of which is not clearly elucidated, and pyrites in raspberry-like clusters (often also present in the calcareous gravels), measuring approximately 10 µm, suspected of contributing, by their oxidation, to the formation of secondary ettringite (Deloye and Louarn (28)). This phenomenon is now being verified at the LCPC.

Finally, while degradations are more common in decks, the forms, composition and location of the reaction products are the same no matter which part is affected.

## 5. CONCLUSIONS

This assessment of the observations of nineteen damaged structures concerns both the alkali-aggregate reaction and the sulphate reaction.

### 5.1. The alkali-aggregate reaction

Three categories of products are distinguished : amorphous (50%), semi-organized (25%), and crystallized (25%). The hypothesis of an amorphous-crystalline evolution emerges from many observations. Polymorphous products would seem to be a step in the crystallization of amorphous products. All of these products are found, in the same proportions, regardless of the age and the type of the structure. This tends to prove that the reaction is still active in all the surveyed structures (Zelwer (29)).

The location of the reaction products is not characteristic of their microtexture. Nevertheless amorphous products are found mainly at the paste-aggregate interface and occasionally in the cement paste, while crystals are generally found in cracks of calcareous aggregates.

The proposed classification, based on textural considerations, is supported by the results concerning the composition of the products : the potassium content and the  $H_{Si}/H_{Ca}$  ratio increase as the crystallographic organization becomes more marked.

All the gravels used in the affected structures are reactive. The sands most often contribute to the degradation. Nearly all the cements involved have a high alkali content and the concretes most often exhibit an alkali content exceeding  $3.5 \text{ kg/m}^3$ . Feldspars, clays and weathered micas could be another source of the alkalis contained in alkali-aggregate reaction products.

### 5.2. The sulphate reaction

Secondary ettringite comes in many forms : the most common are compressed ettringite and ettringite in packets, at the paste-aggregate interface.

When space allows, secondary ettringite occurs as a tangle of clearly individualized long needles. Otherwise, it is compressed, even compact. Its microtexture seems to depend basically on the space available at the time of crystallization.

Findings of large quantities of secondary ettringite when the only source of sulphates is the cement show that primary ettringite, initially distributed in the paste, redissolves to form this secondary ettringite (Poole (30)). In other cases, in addition to the external medium, sulphates from the oxidation of the poorly crystallized aggregate pyrites may be blamed.

The sulphate reaction is much more discreet in structures less than ten years old : its kinetics can be especially slow.

### 5.3. General results

The two foregoing reactions are present simultaneously in almost all the surveyed structures. Within a degraded structure, the distribution of degradation products is highly heterogeneous : some cores may be free of all products ; one or the other of the reactions may predominate in other samplings ; finally, a broad range of microtextures may be concentrated in a single microscopic preparation.

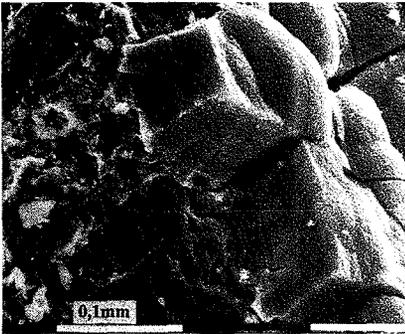
The depth of sampling with respect to the surface of the structure does not modify the microtexture, composition, or location of the reaction products. On the other hand, their occurrence frequency is lower in the first five centimetres. Binder-aggregate reactions may be present inside a structure without the skin of the concrete necessarily containing degradation products (leaching of the alkalis ? faster drying at the surface ?).

The age of the structures, the building materials, and the type of structure do not substantially alter the microtexture of the degradation products. Prestressing seems to increase the share of the products present in the bubbles of the cement paste. This phenomenon was observed in the four prestressed structures studied. No difference is found as a function of the damaged part of the structure. The degraded zones are always exposed to high humidity.

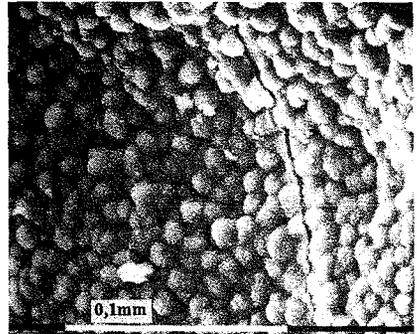
The expert appraisals allowed early detection of the binder-aggregate reactions and an evaluation of the condition of the structures. However, the importance of this type of pathology should be put in context. In France, he two hundred, or so, suspected bridges represent about 0,5% of the total concrete structures : this situation is not alarming but remains a source of concern. Two parallel and complementary attitudes must therefore be assumed : preventive action to eliminate these phenomena (LCPC (31)), and action in response to the degradation of the structures, to optimize their maintenance. Our work has been done in this last context.

### REFERENCES

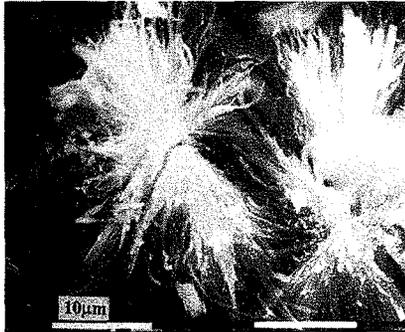
- (1) Corneille, A., Durability of concrete structures, ENPC training session, 2-4 March 1988.
- (2) Godart, B., 20-21 June 1989, Binder-aggregate reactions in concretes, ENPC study sessions, Paris, France.
- (3) Deloye, F.X., 1978, LCPC 83 Report, Laboratoire Central des Ponts et Chaussées, France.
- (4) Deloye, F.X., and Divet, L., 1991, Alkali-aggregate reaction in concrete, 9th International Conference, London, U.K., forthcoming.
- (5) Baronio, G., and Berra, M., 1989, Alkali-aggregate reaction, 8th International Conference, Kyoto, Japan, 71.
- (6) Blight, G.E., 1989, Alkali-aggregate reaction, 8th International Conference, Kyoto, Japan, 733.
- (7) Chatterji, S., 1989, Alkali-aggregate reaction, 8th International Conference, Kyoto, Japan, 37.
- (8) Hobbs, D.W., 1989, Alkali-aggregate reaction, 8th International Conference, Kyoto, Japan, 31.
- (9) Ludwig, U., 1989, Alkali-aggregate reaction, 8th International Conference, Kyoto, Japan, 583.
- (10) Regourd-Moranville, M., 1985, Concrete and water, seminar organized by the Collège International des Sciences de la Construction, Saint-Rémy-lès-Chevreuse, France.
- (11) Bérubé, M.A., and Fournier, B., 1986, *Canadian Mineralogist* 24, 271.
- (12) Carse, A., and Dux, P., Alkali-aggregate reaction, 8th International Conference, Kyoto, Japan, 25.
- (13) Dron, R., 1990, *Bull. liaison Labo P. et Ch.* 166, 55.
- (14) Larive, C., 1990, rapport des laboratoires OA 6, Laboratoire Central des Ponts et Chaussées, France.
- (15) Oberholster, R.E., 1983, Alkalis in concrete - Research and Practice, 6th International Conference, Copenhagen, Denmark, 419.
- (16) Ohama, Y., Demura, K., and Kakegawa, M., 1989, Alkali-aggregate reaction, 8th International Conference, Kyoto, Japan, 253.
- (17) Regourd-Moranville, M., and Hornain, H., 1986, Concrete Alkali-Aggregate Reaction, 7th International Conference, Ottawa, Canada, 375.
- (18) Samuel, G., Wason, R.C., and Mullick, A.K., 1989, Alkali-aggregate reaction, 8th International Conference, Kyoto, Japan, 235.
- (19) Shayan, A., and Quick, G., 1989, Alkali-aggregate reaction, 8th International Conference, Kyoto, Japan, 475.
- (20) Thaulow, N., Holm, J., and Andersen, K.T., 1989, Alkali-aggregate reaction, 8th International Conference, Kyoto, Japan, 573.
- (21) Baronio, G., 1984, Proc. First Int. Conf. Aggregates (Nice, France), 183.
- (22) Deloye, F.X., Le Roux, A., and Lesage, R., 1983, *Bull. liaison Labo P. et Ch.* 126, 37.
- (23) Dron, R., and Brivot, F., 1989, *Bull. liaison Labo P. et Ch.* 161, 25.
- (24) Le Roux, A., and Cador, C., 1984, *Bulletin de l'Association Internationale de Géologie de l'Ingénieur* 30, 255.
- (25) Diamond, S., 1989, Alkali-aggregate reaction, 8th International Conference, Kyoto, Japan, 83.
- (26) Perruchot, A., Delbove, F., and Dabira, M., 1991, *C.R. Acad. Sci. Paris. t. 312. Série II*, 1539.
- (27) Le Roux, A., 20-21 June 1989, Binder-aggregate reactions in concretes, ENPC study sessions, Paris, France.
- (28) Zelwer, A., January 1991, LCPC internal report
- (29) Deloye, F.X., and Louarn, N., 1989, *Bull. liaison Labo P. et Ch.* 161, 41.
- (30) Jones, T.N., and Poole, A.B., 1986, Concrete Alkali-Aggregate Reaction, 7th International Conference, Ottawa, Canada, 446.
- (31) LCPC, 1991, Recommandations provisoires pour la prévention des désordres dus à l'alcali-réaction.



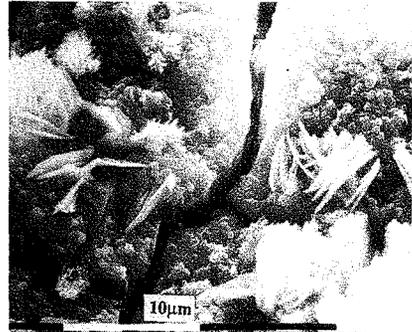
exceptionally thick bump-shaped gel



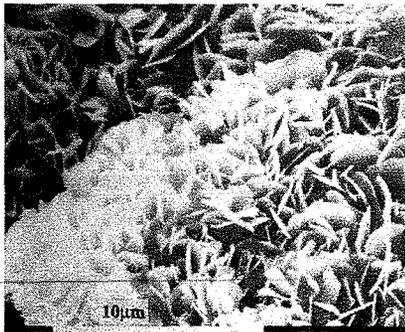
botryoidal product in a bubble



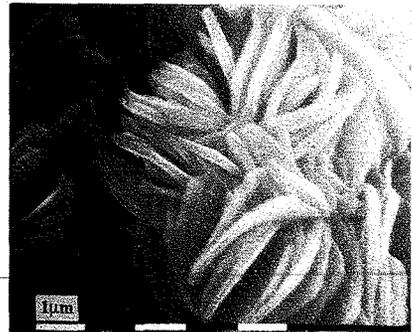
polymorphous product : bunches on smooth gel



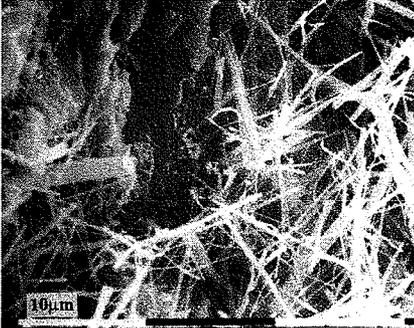
polymorphous product : clumps and lamellae on microgranular product



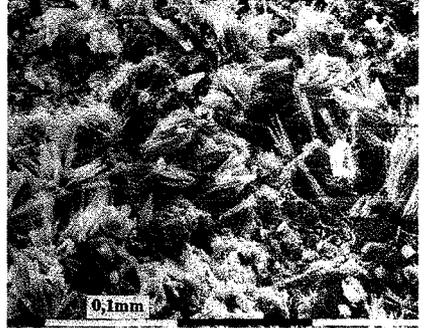
lamellar crystals in a cracked calcareous aggregate



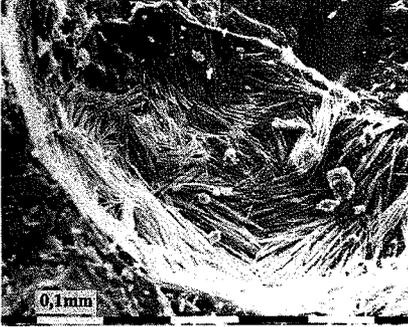
rosette-like crystals in a cracked calcareous aggregate



free ettringite in paste



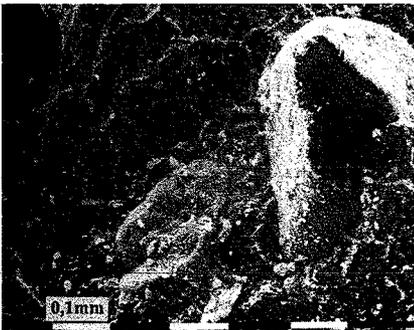
ettringite in packets in paste



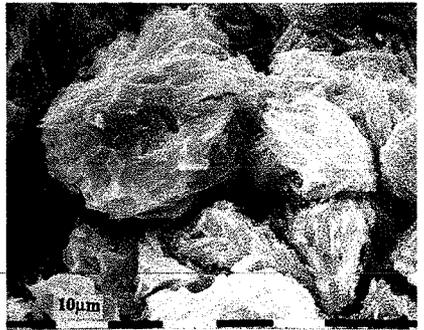
oriented ettringite parallel to an aggregate surface



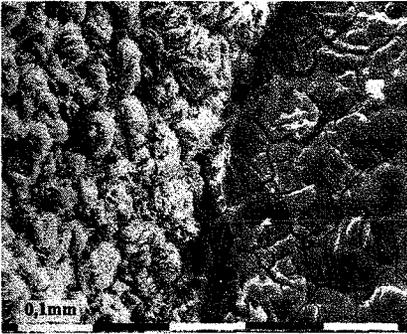
oriented ettringite normal to a bubble surface



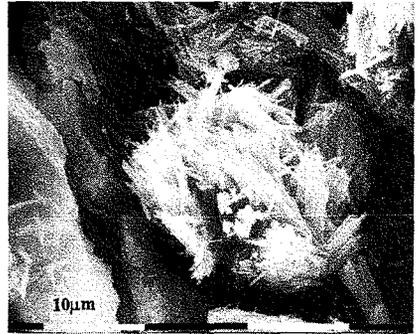
veneer of compressed ettringite on a sand grain



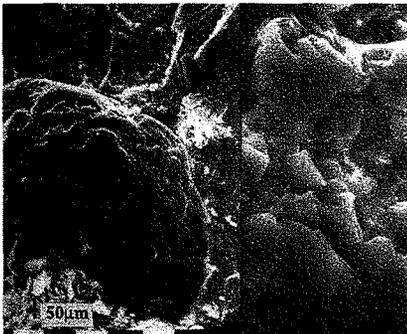
compact ettringite



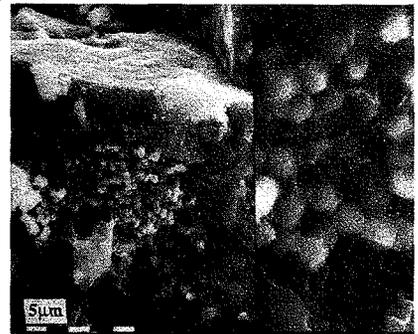
concomitance of smooth gel and ettringite in packets



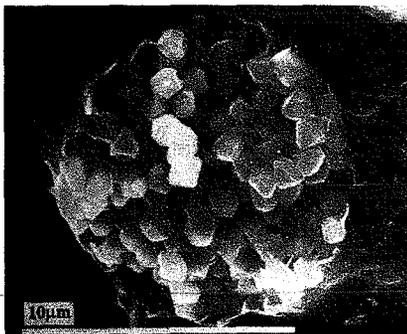
superposition of smooth gel and ettringite in packets



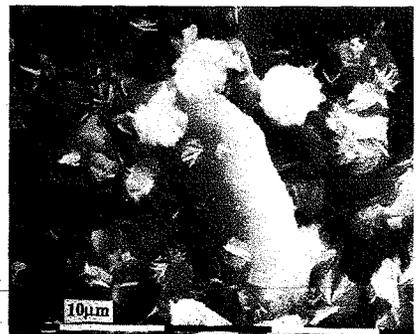
corroded surface of a sand grain and detail of crystallizations of tridymite and cristobalite



pentagonal dodecahedra of pyrites in the paste



pentagonal dodecahedra of pyrites in a calcareous aggregate



silico-calco-potassic lamellar crystals in contact with clay in a calcareous aggregate