FREE EXPANSIONS AND STRESSES IN CONCRETE RELATED TO ALKALI-AGGREGATE REACTION

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Alkali-aggregate reactions can generate significant stresses and strains in concrete structures. In some cases, strains are so great that costly repairs have to be performed. To predict the potential alkali-reactivity of aggregates, free expansion laboratory tests are universally conducted using mortar or concrete prisms, but these tests do not provide any information on the stresses developed in restrain media. To evaluate this particular strain-stress relationship, five reactive aggregates were submitted to free expansion and longitudinal confinement tests. Rock and mortar prisms were stored in NaOH 1N solution at 38°C and 80°C. Results showed that the most expansive aggregate can generate stresses up to 6.5 MPa when using mortar prisms under uniaxial confinement. On the other hand, some dolomitic aggregates stored in NaOH 1N solution at 80°C can generate free expansions and stresses which do not relate exclusively to alkali-aggregate reactivity.

INTRODUCTION

At the present time, expansion tests used to evaluate the potential alkali-reactivity of aggregates, whether accelerated or not, are all based on free expansion limits established for a predetermined testing time. Results showed that alkali-aggregate reactions generate both expansion and stresses in a structure since the expansion occurs in a generally restrained area.

In Canada, there were at least two instances where hydroelectric dams incurred considerable damage due to alkali-aggregate reactions and preventive measures had to be taken. The two dams in question are located in Beauharnois, Québec (Albert and Raphaël (1)) and Mactaquac, N.B. (Thompson (2)). In both cases, transverse cuts had to be performed in order to release the stresses caused by the alkali-aggregate reactions. In Beauharnois, an initial cut made in 1974 immediately closed up. Several other cuts have been performed since then. These two instances demonstrate that the economic implications surrounding alkali-aggregate reactions may be considerable.

Hydro-Québec recently introduced a cutting method using a diamond-impregnated cable in order to release the stresses due to alkali-aggregate or other phenomena in several hydroelectric power plants (Phuong Nguyen, personal comm. (3)).

TABLE 1 - Review of Studies on AAR-related Stresses

Author(s)	Type of test	Type of sample	Aggregate	Stresses (MPa)
Moore (11) Diamond (12)	Physicochemical data	-	-	45-140
Diamond (12)	Estimate	Concrete	-	6-7
Struble and Diamond (13)	Osmotic cell	Synthetic gels	-	10-11
McGowan and Vivian (14)	Uniaxial longitudinal confinement 20°C,100% R.H.	Mortar bars	Opal	0.35
Hobbs (4)	Uniaxial longitudinal confinement 20°C,100% R.H.	Concrete prisms	Opal	4
Houde et al. (15)	Uniaxial longitudinal confinement 38°C	Concrete in steel tubes	Spratt limestone	0.24
Fujii et al. (30)	Uniaxial longitudinal confinement 40°C,100% R.H.	Concrete prisms	Andesite	4
Seno and Kobayashi (17)	Uniaxial longitudinal confinement 40°C,100% R.H.	Mortar in tubes	Glassy andesite	11.8
Wood et al. (19)	Longitudinal confinement through stays	Concrete cylinders	-	13.5
Clergue and Corneille (18)	Triaxial longitudinal confinement	Mortar	Spratt limestone	1
Hydro-Québec (16)	In situ confinement	Dam concrete	Ortho-Quartzite	2
Durand et al. (this paper)	Uniaxial longitudinal confinement	(80°C, NaOH 1N)	Mortar and concrete prisms 3 aggregates	6-7

There are at least four other known cases worldwide of concrete structures where post-stressing was used to maintain the structural integrity of the structures (two in South Africa, one in Japan, and one in Val de la Mare, Jersey) (Hobbs (4)). There have been relatively few studies conducted on the relationship between alkali-aggregate reactions and related stresses, nor is there considerable data available in the literature regarding laboratory and field measurements of strains or stresses attributable to alkali-aggregate reactions (see Table 1). However, before reviewing the current literature, the physicochemical phenomenon which underlies these expansions and stresses is summarized in the following section.

ALKALI-AGGREGATE REACTION (AAR)

Summary of the AAR phenomenon

It was found that the cracks caused by alkali-silica/silicate reactivity resulted from a reaction of Ca^{2+}, Na^{+}, K^{+} and OH^{-} ions in the liquid phase present in the pores of hardened concrete with some siliceous or silicate phases of certain types of aggregates. In the presence of this interstitial solution, which can have a pH as high as 13.0-13.5 (Durand (5)), these phases undergo an attack: some silica is made soluble then combined once again with Na^{+} and K^{+} ions as well as the Ca^{2+} ion in order to form a calcium-silica-alkaline gel. At the same time or immediately thereafter, the absorption of water by this gel generate sufficiently high stresses to make the concrete expand and crack (Dent-Glasser and Kataoka (6)).

As for the alkali-carbonate reaction (argillaceous dolomites), Na^{+}, K^{+} and OH^{-} ions do not react with siliceous or silicate phases but with dolomite and certain clay minerals. No calcium-silicate-alkaline gel is formed; there is rather in situ crystallization of a series of new minerals such as brucite, $Mg(OH)_2$ (Dolar-Mantuani (7)). There can be considerable expansion as a result of such a type of reaction (Swenson and Gillott (8-9) and Rogers (10)).

Theoretical stresses and stresses generated by gel alone

Theoretical stresses. According to research performed by Moore (11), it is possible to estimate potential stresses resulting from osmotic pressure that may be generated by gel produced by alkali-silica reactions (ASR) by using physicochemical data such as the partial vapor pressure of water in the gel and in the interstitial phase, and the partial molar volume of water transferred to the gel (Diamond (12)). According to Diamond (12), who considers these values to be high, these osmotic pressures are between 45 and 140 MPa. Laboratory experiments on synthetic sodium silicate gels and a few gels containing calcium registered about 10-11 MPa maximum (Struble and Diamond (13)).

In practice, the maximum expected stress for concrete subject to ASR does not seem to be overly high and should not exceed 6-7 MPa (12).

Stresses measured experimentally. McGowan and Vivian (14) studied the effects of static loads on the expansion of mortar prisms containing opaline silica as aggregate. Their research has shown that stresses as low as 0.07, 0.14 and 0.35 MPa were sufficient to considerably reduce expansion and delay the development of microcracks. However, when the loads were removed after 112 days, the researchers discovered that a large proportion of the expansion was recovered with respect to the test samples.

As part of another experiment where a 0.35-MPa stress was applied for 112 days, the researchers succeeded in completely arresting any expansion. Similar research conducted by Hobbs (4) revealed considerably greater values than those obtained by McGowan and Vivian (14). By using concrete with an optimal opaline content initially limited to 2.5 MPa, a longitudinal confinement stress of 4 MPa was created. Hobbs (4) attributes this difference to the variation in the rates of free expansion, since the potential stresses increase along with the rate of free expansion.

Other studies conducted by Hobbs (4) have shown that a concrete sample subjected to a stress of 3.5 MPa during 140 days and then released developed an expansion of 0.18% at 200 days compared to 0.5% for a test sample that was not subjected to any stress. Houde et al. (15) performed stress tests with concrete poured into extremely rigid steel tubes. The recorded stress only reached 0.24 MPa despite the fact that a very reactive aggregate was used (Spratt limestone, Canada). Here, a lack of humidity would have impeded alkali-silica reaction.

At Beauharnois, Québec, confinement tests within boring holes revealed stresses of about 2 MPa after a year and a half (Michel Rivest, personal comm.)(16). Seno and Kobayashi (17) studied the stresses developed by mortar cylinders containing a glassy andesite. These mortars, poured into copper tubes, generated stresses reaching 11.8 MPa at 186 days. Clergue and Corneille (18) used a triaxial cell with a calcium silicate aggregate; measurements revealed values of 1 MPa at 28 days.

Wood et al. (19) studied ASR-generated stresses in concrete with varying percentages of steel reinforcement. In one instance, the longitudinal confinement stress reached 13.5 MPa at 75 days for 3.84% of reinforcement. In another instance, the steel became plasticized with only 0.9% of reinforcement. These studies served to pave the way for other research on the relationship between AAR and resulting stresses. This brief literature review allowed us to make the following conclusions:

1. Free expansion, i.e. without confinement, may reach considerable levels in a laboratory setting (e.g. > 1.5%, (4)). During standardized expansion tests, aggregates with values exceeding 0.1% are generally classified as being reactive.

2. The application of stresses may affect expansion and even stop it entirely.

3. In a laboratory setting, longitudinal confinement stresses, i.e. those generated by specimens that were mechanically confined (frames, tubes, reinforcement or hydraulic pressures), can attain values as much as 13.5 MPa.

4. Expansion may occur after stress is removed.

5. In theory, ASR-produced gel may generate osmotic pressure between 45 and 140 MPa.

6. The stresses generated in laboratory by the osmotic pressure in the synthetic gels can attain up to 10-11 MPa.

7. Diamond (12) estimates the maximum pressure in a real structure to be probably around 6-7 MPa.

PRESENTATION OF THE STUDY

Research has been conducted at Montréal's École Polytechnique in order to study the relationship between the expansion of reactive rocks and the resulting stresses. For experimental purposes, rock and mortar test specimens were made with four different types of aggregates. The test program is described in Figure 1.

Materials

Aggregates. Four types of aggregates from five different sources have been used:

A) A slightly siliceous limestone from the region of Trois-Rivières (Québec), Canada;

B) A slightly siliceous limestone from the region of Ottawa (Ontario), Canada;

C) A dolomite from the region of Montréal (Québec), Canada;

D) A green schist from the region of Sherbrooke (Québec), Canada, and

E) A nepheline syenite from the region of St-Hilaire (Québec), Canada.

Trois-Rivières limestone (Québec). The Trois-Rivières aggregate is a fine-grain limestone, with very little clay content, and fossil-rich zones. Some of these fossils consist of silica (sponge needle networks and scolecodonts), while others are totally or partially silicified (brachiopods). Phosphate fossils are also present. The most reactive lithologies in this type of rock are those where one finds finely divided silica throughout a microspar matrix mixed with some clay (Durand and Bérard (20)).

From a mineralogical point of view, this aggregate is very rich in calcite and its insoluble part (4-13% depending on the horizons) primarily consists of illite, particles of quartz and felspar, as well as a little chlorite, dolomite and pyrite. To this is added the wholly or partially silicified fossils mentioned above.

From a stratigraphic point of view, the Trois-Rivières limestone belongs to the St-Casimir Member of the Middle Ordovician Period which is part of the Neuville formation of the Trenton group (Clark and Globensky (21)).

Ottawa limestone (Spratt). The Ottawa aggregate is a limestone that is very similar to the Trois-Rivières one. It is also fine-grain, with very little clay or silicate, with zones that are very rich in fossils. From a stratigraphic perspective, the Spratt limestone belongs to the Bobcaygeon formation of the Middle Ordovician period.

These two aggregates are known to be alkali-reactive (Durand (5) and Bérubé and Fournier (22)). In damaged structures, they exhibit a similar type of reactivity, i.e. one finds calcium-silica-alkaline gel in the form of veinlets within the particles (see Fig. 4), gel in the pores and the cement paste cracks, and gel on the surface of the structures.

Montréal dolomite (Québec). This fine-grain dolomite primarily consists of dolomite rhombohedrons; it may contain up to 20% of small quartz and chalcedony particles. There are not many argillaceous minerals. The limestone is part of the Beauharnois formation in the Beekmantown group of the Middle Ordovician Period (Globensky (23)).

In structures where this aggregate was used, no major reactivity has been noted up to now except maybe for the Carillon dam in Carillon (Québec), Canada (Jean Bérard, personal comm. (24)). Bérard reported that he had observed siliceous gels in the concrete of this dam and other structures containing Beekmantown dolomite. During standardized laboratory expansion tests at 38°C, Blanchette (25) obtained little expansion using this type of dolomite (0.041% at 1 year, with the CSA limit being 0.04% at 1 year). However, at 80°C, Blanchette observed an expansion equal to 0.130%. Thus, low alkali-reactivity may be added to unstable behaviour at high temperature.

Sherbrooke aggregate (Québec). The Sherbrooke aggregate is a green chlorite schist primarily consisting of meta-basalt particles. It also contains small particles of quartz, felspar, chlorite, sericite and other lesser-known minerals. The main reactive phase of this aggregate is probably microquartz, though this rock is usually classified as belonging to the alkali-silica/silicate reactivity category. Grattan-Bellew (26) attributed this aggregate's reactivity to particles of quartz of 15-60 µm which showed undulatory extinction when seen through an optical polarizing microscope.

The alkali-reactivity of the Sherbrooke aggregate is of the internal peripheral type, meaning that the alkaline attack begins peripherally and then progresses inwards. In damaged concrete, the gel may be observed at the paste-aggregate interface and within the aggregate itself. A reactive rim develops along the inner particle circumference. Elsewhere as usual, gel is found in the pores and cracks of the paste and occasionally in the external surface of the structure. It would seem that this aggregate's reactivity is slower than with siliceous limestones, but expansion and cracking may be considerable over the long term (10 years and more).

Saint-Hilaire syenite (Québec). This medium to coarse grains intrusive basic aggregate consists of crystals intergrown with alkaline feldspars, feldspathoids (nepheline) and alkaline pyroxene (aegirine). This aggregate does not contain any quartz and is rich in alkaline minerals. This type of rock was used as an example of an aggregate that is non-alkali-reactive under normal test conditions. However, during testing at 80°C in a solution of NaOH 1N, low expansion percentages were obtained.

Mixture characteristics

The mixture required in ASTM standard C227 (27) was used, except for the W/C ratio which was set at 0.45 rather than having to adjust it according to the desired flow. The initial curing method used is the one described by Oberholster and Davies (28) for testing accelerated expansion of mortar prisms. A type-10 portland cement was used for the latter, and the alkaline content was increased by 0.92% at 1.25 equiv. Na_2O by adding NaOH to the mixing water.

TEST DESCRIPTION

As a first step, free expansion and longitudinal confinement tests were conducted on rock prisms using the Trois-Rivières limestone and the Montréal dolomite. The specimens were placed in a solution of NaOH 1N, first at 38°C during about five weeks, followed by 80°C. The test assembly is shown in Figs. 2, 3 and 5. A steel structure (plates, bolts, tie rods and screw rods) was built for the longitudinal confinement tests. Load cells were used to measure the resulting loads. Free expansion was measured in air using a dilatometer, while load readings were performed in situ at 80°C.

For the Trois-Rivières aggregate, the prisms that were used were cut into several parallel sections. Each cutting surface was polished with 240, 400 and 600 mesh abrasives, after which the prisms were reassembled. This special technique was used in an attempt to reproduce the formation of gel veinlets within the microcracks in a natural setting. Thus, by artificially creating discontinuities, the creation or appearance of gel was anticipated to be favoured.

Monolithic prisms were built for the dolomite since the reaction mechanism is homogeneous throughout the aggregate's mass and is not limited to the circumference or to previously formed microcracks.

As a next step, free expansion and longitudinal confinement tests were performed using Ottawa limestone, Sherbrooke schist and Saint-Hilaire syenite. The curing process lasted 30 days in a solution of NaOH 1N at 80°C. Procedures used were the ones described in the South African accelerated expansion test (28) which is in the process of being standardized in Canada. The set up used for the longitudinal confinement was similar to the one previously described.

For all longitudinal confinement tests, an small initial load was applied in order to maintain the specimens in place. The values indicated on the graphs consider the initial load as being nil.

RESULTS

Rock prisms

Figures 6 and 7 show the overall results obtained for free expansion and longitudinal confinement tests for the rock specimens. The load or expansion development only began when the specimens were subjected to 80°C. In both cases, the resulting expansion and stresses are considerable, but the shape of the curves differs, i.e. convex for the Trois-Rivières limestone and concave for the Montréal dolomite. Specific observation of the specimens confirmed the appearance of two expansion mechanisms. For the Trois-Rivières limestone, the gel formed on the surface of the specimens, particularly at each of the interfaces which had been artificially created through cutting and polishing. By separating the various sections of the specimens it was possible to observe a morphology that is typical of gel (distribution and type) as is usually observed in concretes. In the middle, a clear and not very thick gel could be observed and, close to the internal rim, a whitish, ring-shaped and rather thick gel could be found. No cracks were noted in the specimen which had been subjected to free expansion, while cracks parallel to the axis of the load appeared towards the end of the longitudinal confinement test (120 days). Only a whitening of the surface was observed for the dolomite with respect to the reaction products. However, after a certain time, many microcracks appeared, both in free expansion and longitudinal confinement.

Dolomite reached the highest value in free expansion, i.e. 3.4% compared to 1.1% for the limestone. However, the limestone reached a stress level of 4.0 MPa while the dolomite reached 3.3 MPa.

Mortar bars

Figures 8 and 9 show the results obtained for the free expansion and longitudinal confinement tests with respect to the mortar specimens. It can be observed that expansion and stresses occured right at the start of the tests and a rapid progression takes place with respect to the reactive aggregates. Syenite showed some reactivity, which remained at a low level. After 14 days, some exudation of whitish matter on the surface of the specimens made with the Ottawa limestone and the Sherbrooke schist were observed; however, no microcracks were present.

This time, it was the most expansive aggregate which developed the greatest stresses, i.e. 0.39% vs. 4.5 MPa for the Ottawa limestone, and 0.25% vs. 3.5 MPa at 14 days for the Sherbrooke schist. The results presented are fairly restricted in number and will have to be confirmed by additional tests which are underway at the École Polytechnique. A more elaborate research program involving concrete specimens has been undertaken but the results are not available yet.

DISCUSSION AND CONCLUSION

The results, albeit preliminary, that were obtained have confirmed that:

1. The alkali-aggregate reactions may generate considerable free expansion and longitudinal confinement stresses.

2. The alkali-reactivity mechanism may vary from one aggregate to another. In addition, in the case of dolomite, it would seem that a very high temperature in an alkaline solution (80°C, NaOH 1N) may generate expansions and stresses that are not solely due to alkali-aggregate reactions. The susceptibility of certain dolomites to high temperatures has already been described in the literature (25,29).

3. For siliceous limestones that react by forming veinlets of calcium-silica-alkaline gel, the results show that it is possible to quite accurately reproduce the phenomenon with respect to the discontinuities created artificially. It would seem likely that most of the expansions or stresses measured could be attributed to the formation of gel with respect to these discontinuities. However, it has not been proven that this could be applied to the actual phenomenon occurring in real concrete. Additional tests will be performed in order to verify this hypothesis.

4. The use of mortar prisms at 80°C and in NaOH 1N enabled us to obtain longitudinal confinement test results within a short period of time, just as in the case of free expansion. According to the results obtained, the aggregates which showed the greatest degree of free expansion generated the highest stresses. Tests are currently being conducted in order to confirm this hypothesis.

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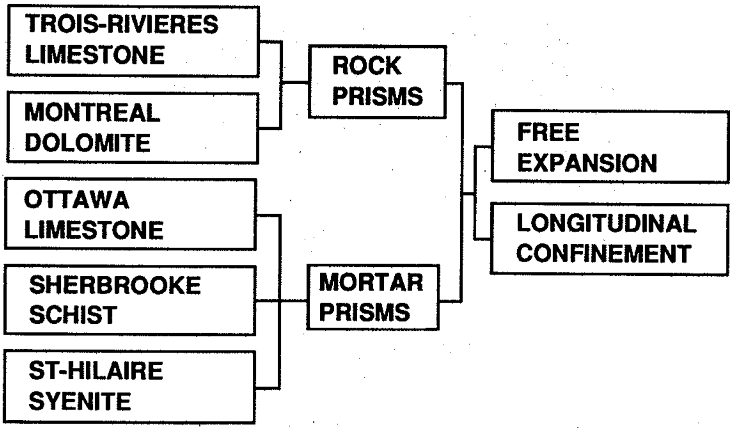
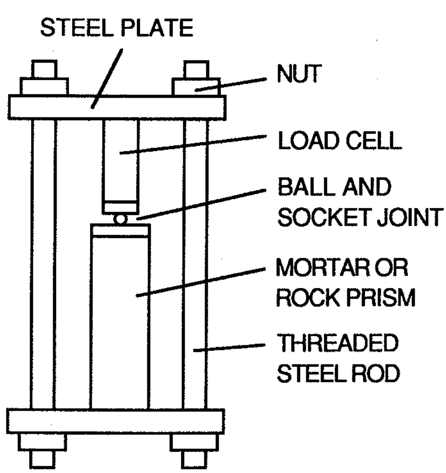


Fig. 1: Test program



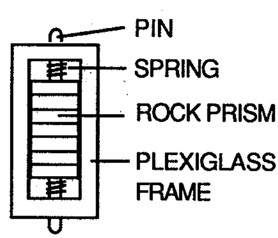


Fig. 2: Longitudinal confinement test assembly

Fig. 3: Rock prism free expansion test assembly

Fig. 4: Photograph of a limestone aggregate with numerous calcium-silica-alkaline gel veinlets (cut and polished surface area, 1.8x)

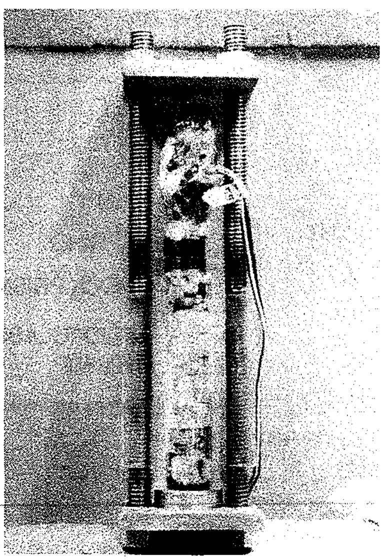


Fig. 5: Photograph of the longitudinal confinement rock prism test assembly

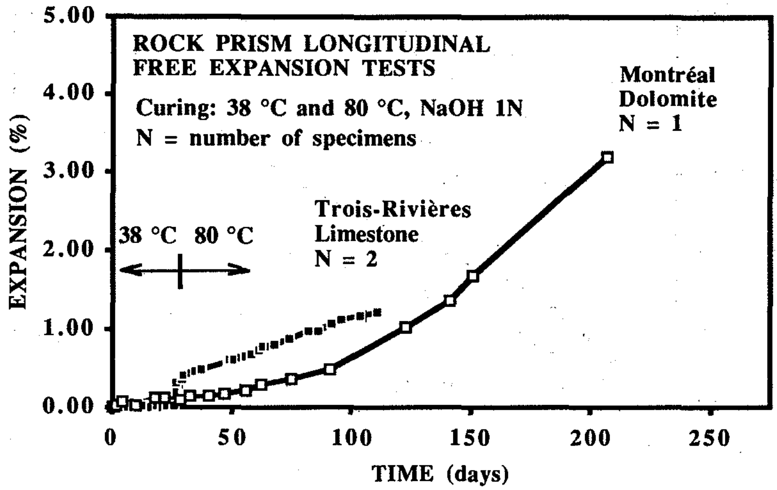


Fig. 6: Evolution of rock prism free expansion

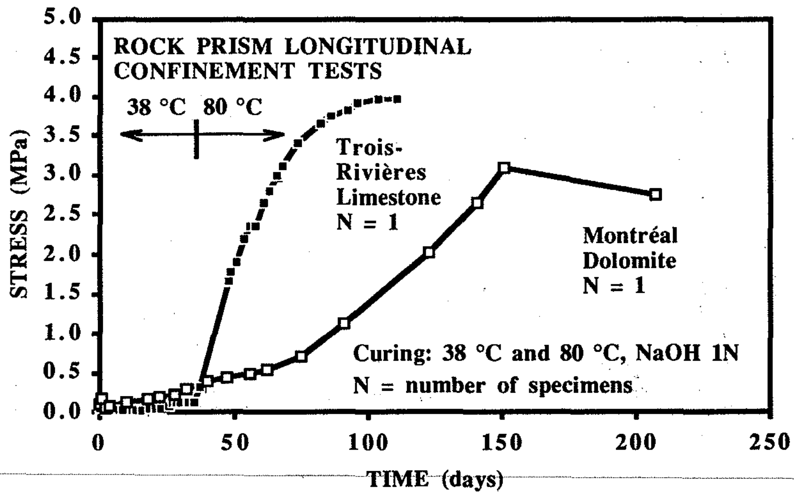


Fig. 7: Evolution of rock prism longitudinal confinement stress

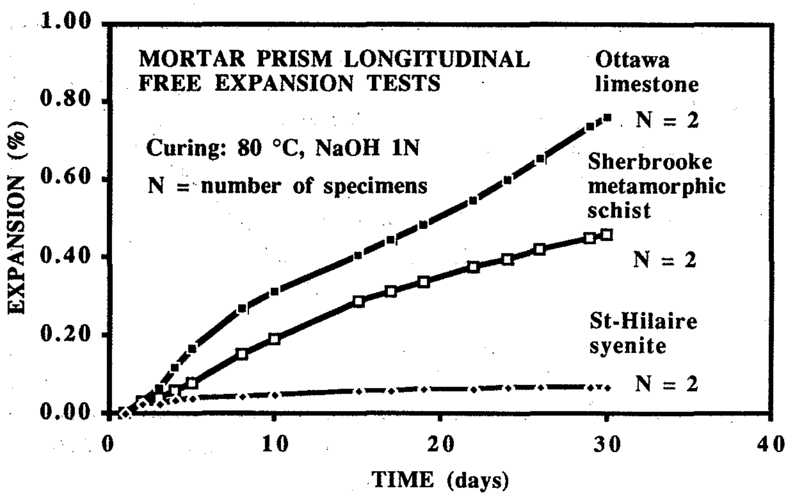


Fig. 8: Evolution of mortar prism free expansion

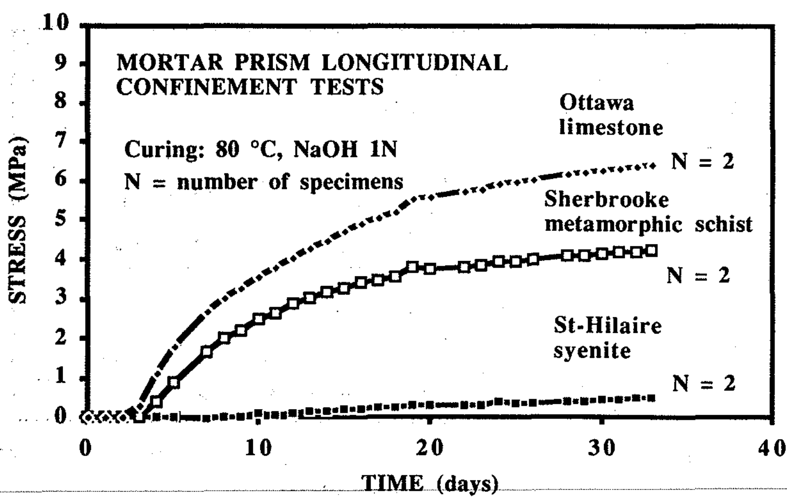


Fig. 9: Evolution of mortar prism longitudinal confinement stress