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HETEROGENEITY AND ANISOTROPY IN ASR-AFFECTED CONCRETE CONSEQUENCES FOR STRUCTURAL ASSESSMENT

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ABSTRACT

Swelling due to Alkali-Silica Reaction is most often evaluated by measuring one or maximum three deformations on a few specimens (usually sets of three concrete prisms are used). Values are always more or less dispersed but it is difficult to have a precise idea on the real ASR heterogeneity.

In this paper, both the heterogeneity and the anisotropy of swelling due to Alkali-Silica Reaction are quantified on numerous concrete specimens. Comparison is made with non-reactive specimens. Explanations on the origin of these phenomena are given and consequences on structure assessment are discussed.

Keywords: Alkali-Silica Reaction, expansion, heterogeneity, anisotropy, structure.

INTRODUCTION

Aggregate reactivity as well as potential residual expansion of ASR-affected concrete are often based on swelling measurements. Usually, one to three measurements are performed on one to three specimens. Concrete prisms as well as cores expansion are most often both measured perpendicularly to the casting direction.

Before extrapolating this kind of results to assess structures' behaviour, it is necessary to:

- Quantify ASR heterogeneity,
- Compare expansions in the casting direction and perpendicularly,
- Take into account the effect of mechanical stresses (Larive 1998),
- Compare expansion for various specimen sizes.

This paper brings an answer to the first two points.

EXPERIMENTAL CONDITIONS AND METHODS

Materials and Storage Conditions

Many reactive and non-reactive concrete cylinders (24 cm high, 13 cm in diameter) have been cast, kept 14 days at 23°C under aluminum foils (no water exchange) and then stored at 23°C or 38°C in high humidity (95 to 100% Relative Humidity).

The materials and the concrete mixture design (Table 1) have been chosen to be similar to those used in some affected French bridges. The cement content is 410 kg/m^3 and the aggregate are siliceous limestone known for their reactivity (containing 20% of reactive silica) or non-reactive reference limestone.

TABLE 1: Concrete Mixture Design

Materials	Weight (kg/m3)
Cement	410
Coarse aggregate (6-12,5 mm)	1050
Fine aggregate (0-6 mm)	700
Water (total)	196.8

The cement used is an Ordinary Portland Cement containing 1.13 % Na_2Oeq. The total alkali content has been adjusted to 1.25% (5.125 kg/m^3) by adding potassium hydroxide to the mix water (for both reactive and non-reactive concrete).

Measurement Methods

Expansion measurements have been performed in both longitudinal and transverse directions of the cylinders.

Longitudinal expansions have been measured on three generating lines with a ball extensometer equipped with an inductive displacement sensor (LVDT). The standard uncertainty has been calculated, taking into account all the uncertainty sources including reproducibility with various operators. The standard uncertainty is 20 µm/m for one measurement on a single generating line; it is 11 µm/m (0.0011%) for the average of three generating lines measurements, as performed on each cylinder (Larive 1998).

The transverse measurements have been achieved by using a specific device allowing obtaining simultaneously up to 30 diameter values for each specimen (Joly et al. 1994). This devise is also equipped with LVDT inductive displacement sensors (Fig. 1) and the standard uncertainty has also been calculated (the influence of the operator is particularly low). Its value is 24 µm/m for one measurement on a single diameter; it is 5.6 µm/m (0.00056%) for the average of thirty measurements, as performed on each cylinder (Larive 1998).

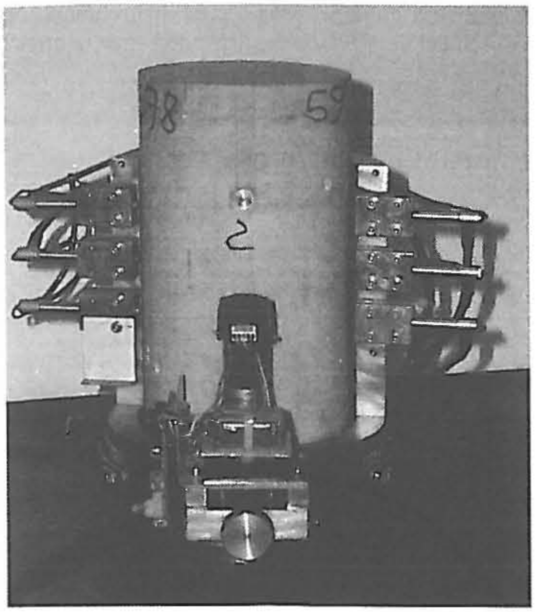


Fig. 1: LCPC diameter variations measurement device

When expanded uncertainty (k = 1.96) is represented like an error bar on graphs, it means that the true value has 95% probability to be inside the bar.

Specimens have also been weighed in order to evaluate water exchanges (resolution: 0.1 g, maximum permissible error (k=2): ±2 g).

RESULTS AND INTERPRETATION

Intrinsic Heterogeneity

Even when only three measurements are performed on three generating lines of concrete cylinders, dispersion is very variable from one specimen to an other (Fig. 2). Dispersion can be as high as the difference between the maximum and the minimum average swelling of thirty-six specimens.

When numerous specimens are compared, it is difficult to assess whether this dispersion is due to the materials or can be attributed to heterogeneous storage conditions (variable humidity in the six humid enclosures used). When thirty diameter variations are measured on the same specimen (on thirty-six different specimens), the same or even a higher dispersion can also be observed (Fig. 3). Heterogeneity remains variable from one specimen to another one : **the ratio between the highest and the smallest transverse expansions varies from 1.5** (specimen 488) **to 2.35** (for specimen 481).

This heterogeneity can be attributed to the heterogeneous repartition of the reactive silica inside the limestone aggregate. It cannot come from heterogeneous storage conditions because the thirty transverse swelling measurements have been performed on the same specimen kept in a homogeneous humid environment. Neither is it due to the precision of the measurement device (see the expanded uncertainties on Fig. 2 & 3).

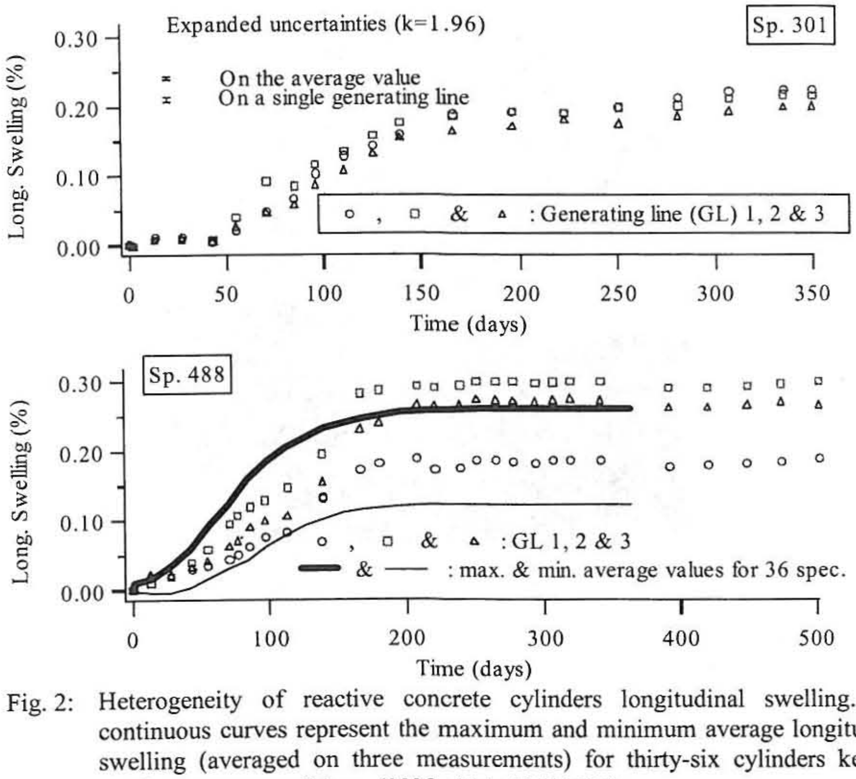


Fig. 2: Heterogeneity of reactive concrete cylinders longitudinal swelling. The continuous curves represent the maximum and minimum average longitudinal swelling (averaged on three measurements) for thirty-six cylinders kept in similar storage conditions (38°C, 95 to 100% RH).

Fig. 3A shows that, even for one of the less heterogeneous specimens, heterogeneity is far superior for reactive than for non-reactive specimens. Fig. 3B shows that the transverse swelling measurements cannot be distinguished by their location on the specimen: values in the middle of the specimen, 3.5 cm below and 3.5 cm above are not significantly different.

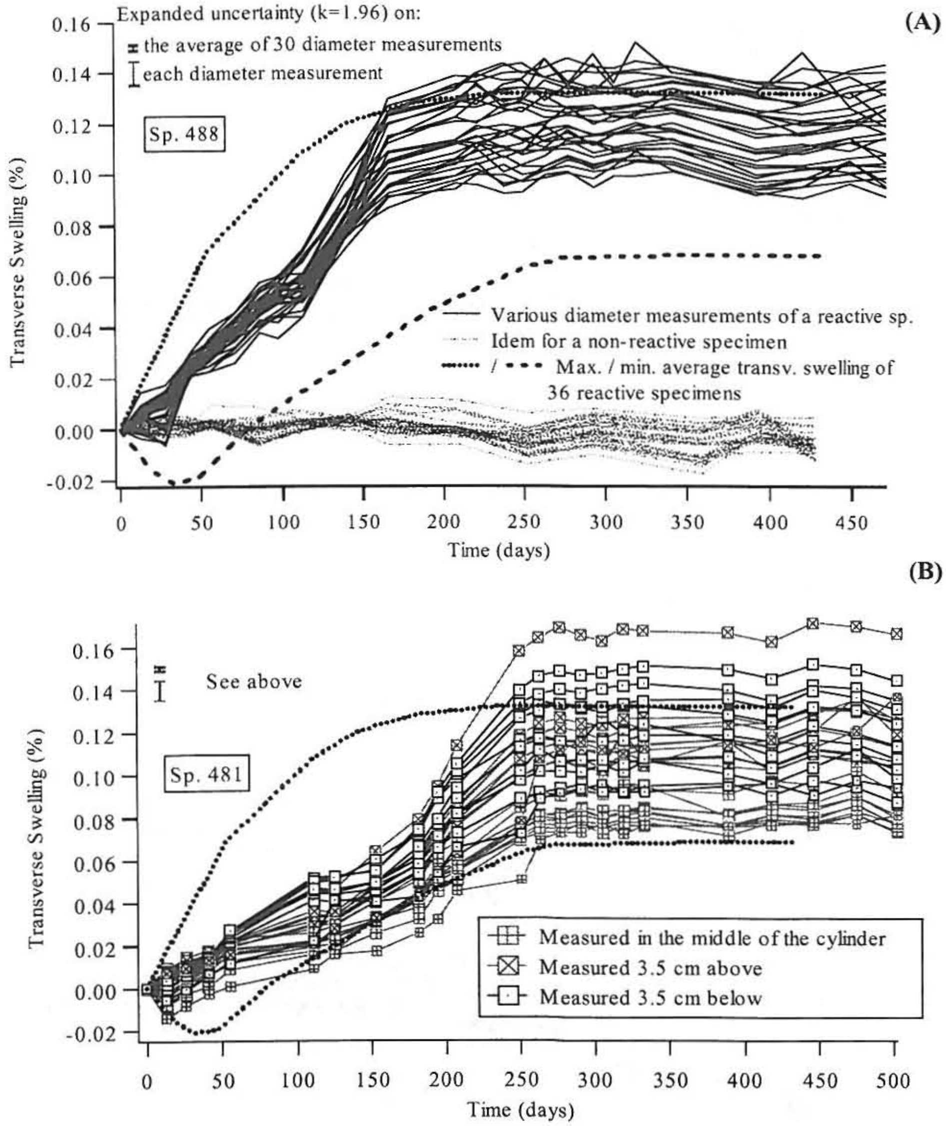


Fig. 3: Heterogeneity of reactive concrete cylinders (24 cm high, 13 cm in diameter) transverse swelling. The dash curves represent the maximum and minimum average transverse swelling (averaged on thirty measurements) for thirty-six cylinders kept in similar storage conditions (38°C, 95 to 100% RH).

Anisotropy

The transverse and longitudinal swelling amplitude has been compared on concrete cylinders at 38°C and 23°C in high humidity (95 to 100% RH). Fig. 4 shows that the average longitudinal swelling is far higher than the transverse one at both temperatures.

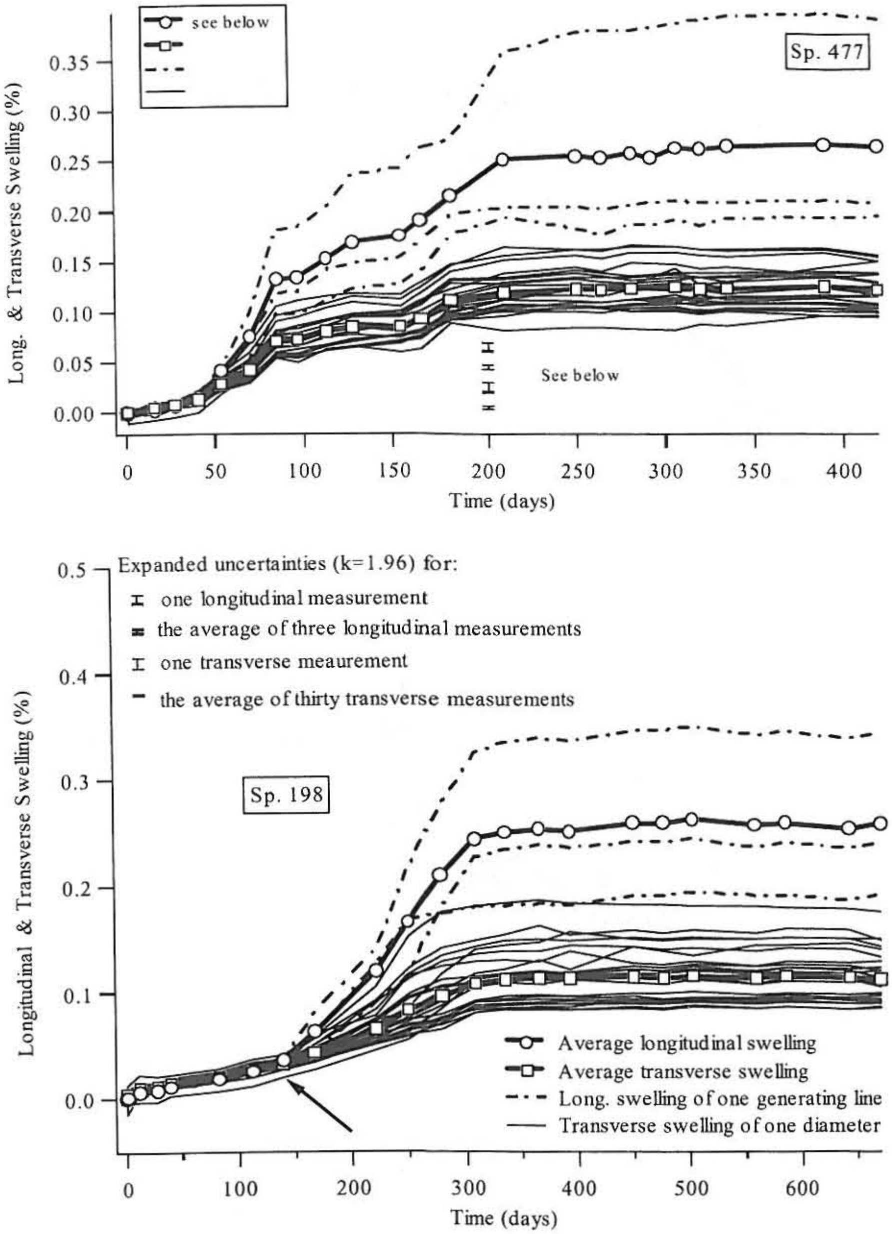
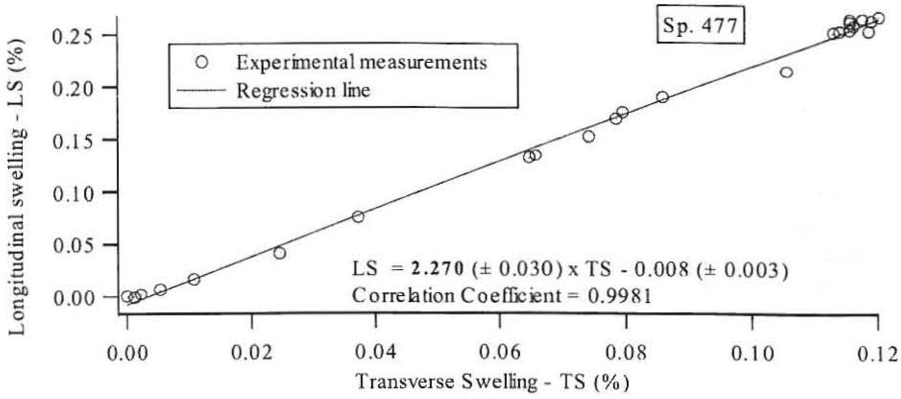


Fig. 4: Longitudinal versus transverse swelling for sp. 477 at 38°C and sp. 198 at 23°C

The average values of the longitudinal versus the transverse swelling have been systematically plotted at both 38°C (36 reactive / 4 non-reactive specimens) and 23°C (10 reactive / 3 non-reactive specimens) (see Fig. 5 for an example & Table 2 for a complete survey).



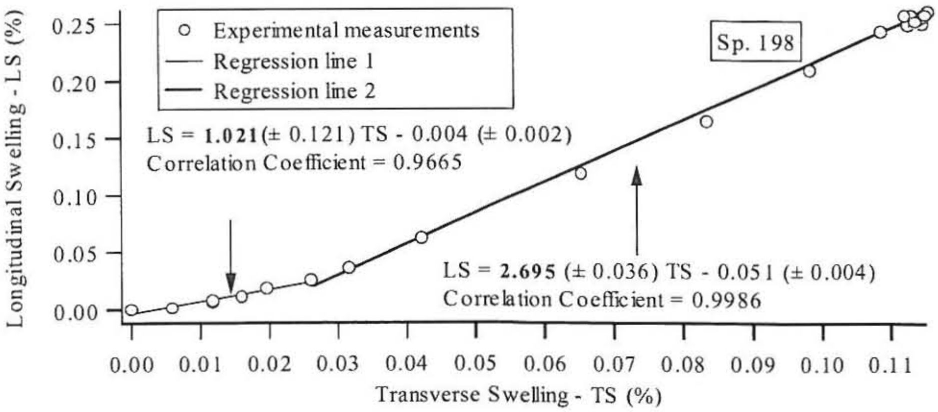


Fig. 5: Long. and transverse swelling vs time for sp. 477 at 38°C and sp. 198 at 23°C

The cylinders' swelling is obviously anisotropic (fig. 4, 5 & Table 2). Such results had already been found (Jones and Clark 1996) but never explained. It should also been noticed that, in their state-of-the-art review of numerical simulations of concrete dams expansion, Léger et al. (1995) had mention "the highly anisotropic nature of the expansion process".

For every specimen at 23°C, the swelling is systematically first isotropic (for example during 150 days for sp. 198 on Fig. 5) then anisotropic when the longitudinal swelling exceeds about 0.02%, which corresponds to the appearance of noticeable cracks.

Anisotropy can be related to the preferential horizontal orientation of the cracks. It can actually be observed that, although specimens are progressively covered by map cracking, horizontal cracks appear first and are more numerous and wider than the vertical ones (Fig. 6) (Larive 1998).

TABLE 2: Slopes and Correlation Coefficients for the Linear Relation between Longitudinal and Transverse Swelling of 46 Reactive and 7 Non-Reactive Specimens at 38°C or 23°C

	Storage temperature	R/NR	Slope	Correlation Coef.	Spec. nb
Maximum			2.679	**0.999**	
Average			1.936	**0.99**	
Minimum	38°C	reactive	1.281	**0.956**	36
Std dev.			0.300	**0.012**	
Maximum			2.695	**1.000**	
Average	23°C	reactive	1.971	**0.997**	10
Minimum			1.294	**0.992**	
Std dev.			0.506	**0.003**	
Maximum			*0.317*	***0.594***	
Average	*38°C*	***non-reactive***	*0.242*	***0.444***	*4*
Minimum			*0.152*	***0.284***	
Std dev.			*0.069*	***0.129***	
Maximum			*1.378*	***0.868***	
Average	*23°C*	***non-reactive***	*0.824*	***0.792***	*3*
Minimum			*0.592*	***0.074***	
Std dev.			*0.200*	***0.72***	

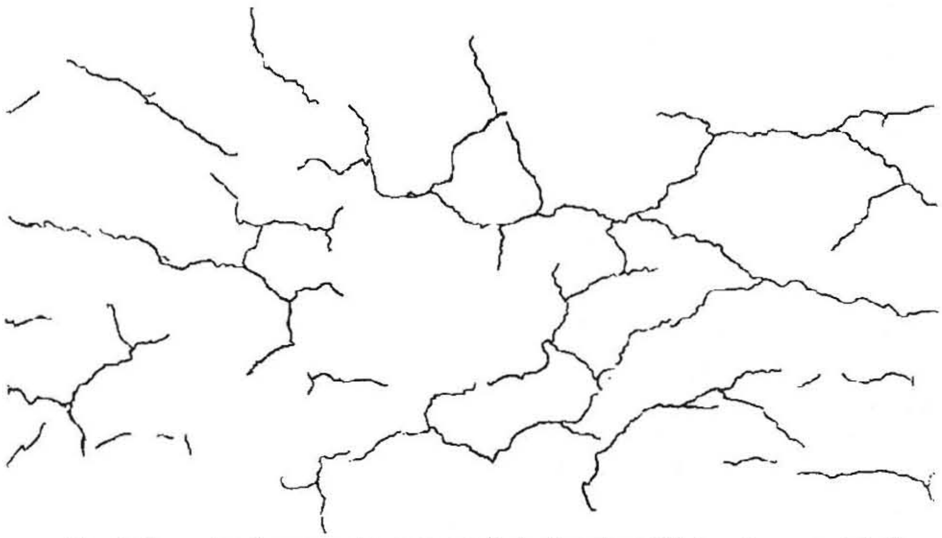


Fig. 6: Example of map cracking on a cylinder (cracks width is not representated) - Horizontal cracks are more numerous than vertical ones.

It has been established (Larive 1998) that the origin of the anisotropy is the <u>intrinsic</u> concrete anisotropy due to the vibration during casting (Hughes and Ash 1969): the accumulation of water under the aggregate particles ("water gain") produces porous zones. This leads to anisotropic tensile strength. If aggregates are flaky (which was the case of those we used), anisotropy is higher and, if the ASR-products formation is regular around the aggregate particles, pressure will also be higher in the vertical less resistant direction.

In ASR-affected concrete, intrinsic anisotropy favours horizontal cracks opening and therefore water penetration through these horizontal cracks, thus favouring new products formation in the cracking planes and enhancing preferential horizontal cracks orientation.

These results are confirmed by the comparison of the swelling of cylinders and prisms (Fig. 7). The longitudinal swelling of cylinders (measured in the casting direction) is also about twice the longitudinal swelling of prisms (measured perpendicularly to the casting direction). This result can not be attributed to the storage conditions because, as can be seen on the upper part of Fig.7, the cylinders which have swollen the most have absorbed rather less water than the prisms.

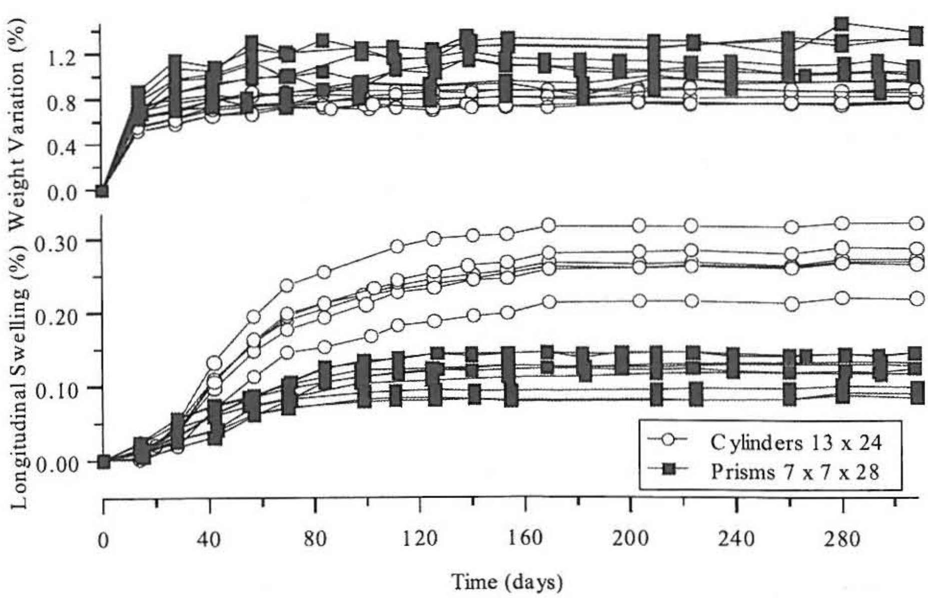


Fig. 7: Comparison between the longitudinal swelling of cylinders and prisms

STRUCTURAL ASSESSMENT - CONCLUSIONS

Residual expansion tests are more and more commonly performed on cores extracted from ASR-affected structures. These tests are very useful to evaluate the ulterior potential swelling of the concrete. Among the major controversial points are:

Point 1: the effects of the core extraction from it original state of stress - For usual state of stress, recovering may probably be considered as negligible compared with expansions due to ASR (Larive, 1998).

Point 2: the representativeness of the cores - Residual expansion tests are too often performed on a small number of cores. As the expansion can at least double from one specimen to an other specimen and from one point to an other point on the same specimen, there are two ways to improve the assessment of the potential ulterior swelling: increasing the number of cores and/or increasing the number of measurements on each core.

Moreover, especially if cores are extracted by horizontal coring, the swelling anisotropy must be taken into account to avoid underestimating the residual potential expansion. This can be achieved by measuring both the longitudinal and transverse swelling, keeping in mind that the smallest dimension of the core must be at least five times higher than the aggregate maximum size.

In the absence of more precise data on a specific mixture design, an average value of two could be used for the ratio between the swelling in the casting direction and perpendicularly. This value is probably overestimated because it has been established using flaky aggregates. It should nevertheless be evaluated for each mixture design because it depends not only on the aggregate form but also on the concrete vibration during the casting.

Finally, while remaining highly useful, the prediction of structural behaviour via any modelling must not be expected to be more accurate than the input information. Provided that anisotropy is taken into account, a result varying from at least 1 to 2 would already very satisfying and helpful for structure management. Probabilistic framework for mechanical modelling could improve the accuracy of the predictions if relevant statistical data are available.

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