

Assessment of the residual expansion potential of concrete from structures damaged by AAR

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Abstract

Residual expansion of cores from several concrete structures with varying degrees of damage has been measured to identify different phases of expansion and to investigate the influence of core size (length and diameter) and the storage temperature on the measured values. The expansion can be divided into different phases with different expansion rates. The results indicate that the expansion in the first phase, that takes place after sample conditioning and but before a linear expansion rate is reached, determines the further behaviour of the cores during the test. Therefore, it can be used to distinguish concrete with different residual expansion potentials. The data analysis shows that the anisotropy between expansion in length and width of the cores generally increases with the slenderness of the cores. However, the anisotropy tendentially decreases with increasing residual expansion values. The residual expansion shows a correlation with the expansion rates on the existing structures assessed by crack width measurements and the expansion of lab concrete, with a similar composition as the on-site concrete, determined with a concrete performance test.

Keywords: alkali aggregate reaction, residual expansion, validation, anisotropy

1 INTRODUCTION

In the assessment of structures damaged by alkali-aggregate reaction, the determination of the residual expansion potential of the concrete plays an important role. Compared to the on-site monitoring of damaged structures, the measurements permit a relatively fast assessment of the concrete's expansion potential in the future. As such, it is an important tool to plan maintenance and the cost involved. However, only few studies deal with the subject [eg. 1, 2, 3]. Consequently, several uncertainties still exist regarding both the methodical approach for such measurements and the data analysis. In most cases, residual expansions are measured under storage conditions of 38°C and 100% RH. But other tests, e.g. in water or NaOH solutions are discussed in [4-7]. There is more or less a consensus about the influence of temperature and humidity but the opinions diverge about which stage of the conditioning and testing the expansions have to be accounted for. Most of the published data of the residual expansion measured at 100% RH and different temperatures show a similar progress of the relative expansion with time. The strong expansion at the beginning is interpreted as moisture uptake depending on the condition of the core and the reaction phase with formation of reaction products and the swelling of already existing gel. The end of the reaction phase is reached as soon as the expansion rate decreases asymptotically [8, 9]. Usually the leaching of alkalis is mentioned as an explanation for this levelling off of the expansion curves. However, the analysis of literature data [9] shows that for many tests with reactive but also non-reactive aggregates, the expansion gradient does not tend towards zero but

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stays constant at a certain level even over years. Since the absolute expansion values can be very high depending on the concrete measured and the duration of the storage, the question arises if these expansions can be taken into account for the interpretation of the residual expansion measurements. Another problem of the measurement data is the anisotropy between longitudinal and diametral expansions which have been often observed and analysed in detail in [7, 8, 17]. In summary, there are several uncertainties in regard to the assessment of the residual expansion potential:

- How do the different parameters like size and temperature affect the measured expansion (Figure 1)?
- How shall the different phases of expansion be taken into account?
- Shall an expansion gradient be used or an absolute expansion value at the end of the test?
- Has the test to be performed for a given time or until the expansion ceases?
- What is the influence of the leaching of alkalis?

This study is part of a larger project dealing with the validation of different test methods used to assess AAR-risk. Beside the residual expansion potential, an ultra-accelerated microbar test for aggregates [10] and the concrete performance test at 60°C according to AFNOR [11] are investigated. The results of the validation of the two other methods are published in [12, 13]. Additional samples were taken to determine concrete properties and concrete composition accompanied by crack-width measurements on the damaged structures. Based on these results, concrete mixtures with a similar composition as the on-site concrete were produced using aggregates from the same quarries as were used for the on-site concrete. They were tested with the already mentioned concrete performance test according to AFNOR (further called CPT, [11]). The results obtained in the residual expansion test have been compared with the degree of damage on the structures and the expansion obtained in the CPT.

2 MATERIALS AND METHODS

2.1 General

Between 25 and 40 years old structures were selected [described in 13] from different parts of Switzerland, covering different geological settings and exhibiting damages due to AAR with the exception of structure GU which was selected as a reference for an undamaged on-site concrete (Table 1). From cores taken in strongly damaged and weakly damaged areas, samples were prepared from deeper zones beyond the carbonation front and without macroscopic cracks. Crack width measurements on the on-site concrete were realised according to the method presented in [14].

2.2 Methods for assessment and analysis

Immediately after sampling, the cores were welded into plastic bags to prevent moisture loss during the transport to the laboratory. The samples were equipped with spindles (in drill hole fixed stainless steel spindles).

The residual expansion potential has been measured on series of three samples with a diameter of 50 and 100 mm and a length of 200 mm, which were stored at a temperature of 38 °C and at 100 % RH, according to LCPC Nr. 40 [15]. The cores have been wrapped in a plastic film because the experience shows, that even in a reactor at 100% RH it is difficult to avoid mass loss. It is not excluded, that the plastic film would have also a protecting effect against leaching of alkalis. Several series of three samples with a diameter of 50 mm and a length of 200mm were additionally stored at a temperature of 20 °C and at 100% RH according to the method described by Wood [3]. Mass changes, longitudinal expansion and crosswise diametral expansion of the cores (Figure 2) were monitored for at least one year (measurements every 4 weeks at 20°C). The test method of residual expansion can be divided into three different phases (Figure 3). In the discussion of the results it is referred to these phases.

Phase 1: The initial measurements of dimension and mass were realised before the samples were conditioned at 20°C in containers with a thin layer of water at the bottom of the container, permitting capillary suction until reaching constant mass (usually after one or two weeks). The water saturation is accompanied with a first swelling of the samples. Phase 2: The cores were stored in the reactor at 38 °C, respectively at 20°C and at 100 % RH. During 30-60 days at the beginning of phase 2 a strong but quickly leveling off expansion could be observed. In the following, it will be designated as "non-linear expansion at the beginning of phase 2". Afterwards, the expansion rate is constant, in certain cases also levels off. This part of the expansion is designated as "linear expansion during phase 2". Generally, only minor mass changes can be observed during phase 2. As the cores of structure MB still displayed a high expansion gradient, the measurements were continued for another year (Figure 5a). Phase 3: After removing the cores from their containers they were dried at 60-70% RH to their initial weight (at the start of conditioning) and the final "irreversible" expansion is measured.

3 RESULTS

3.1 Phase 1: Conditioning of the samples – Water saturation

The samples swell with increasing water saturation. Neither the increase in mass nor the resulting expansions during phase 1 influence the following expansions during the storage in the reactor, as i.e. shown by the non-linear expansion at the beginning of phase 2 (Figure 4a).

3.2 Phase 2: Non-linear and linear expansion

The extent and the duration of the non-linear expansion at the beginning of phase 2 vary between the different concretes. It is decisive for the behaviour of the samples in the further course of the storage. The higher the non-linear expansion rate at the beginning of phase 2, the higher is also the following linear expansion rate during phase 2 (Figure 4b, also applies to the samples stored at 20 °C but which aren't shown here) and the irreversible expansion (Figure 5b).

The non-linear expansion rates of the cores with a diameter of 50 mm is clearly higher than those of the cores with a diameter of 100 mm, while the linear expansion rates are similar for both core diameters (Figure 4b). The longer phase 2 is, the larger the resulting expansions are (Figure 5a).

3.3 Phase 3: Irreversible expansion

The irreversible expansion is measured after drying to the initial mass. It varies depending on the storage conditions, the measurement direction (longitudinal or diametral) and the size of the samples (see Figure 5b). The highest values have been measured diametrically on the cores stored at 38 °C with a diameter of 50 mm (1.5 mm/m). The irreversible expansion also depends on the duration of the storage, especially if the linear expansion rates are high and are not levelling off during the intended storage duration (i.e. structure MB, Figure 5). In this case, the irreversible expansion is unusually high compared to the non-linear expansion rate.

Figure 6a shows that the total expansion (expansion obtained during phase 1 and phase 2 due to the water saturation and expansion during the storage in the reactor) is higher than the irreversible expansion while the expansion during phase 2 (only the expansion in the reactor) is lower than the irreversible expansion. This means that a part of the expansion during the water saturation (phase 1) is irreversible since otherwise the irreversible expansion would be identical with the expansion obtained during phase 2. The part of the irreversible expansion during the water saturation seems to be larger diametrically than longitudinally and generally seems to grow with the increasing irreversible expansion.

3.4 Comparison of the samples with diameter 50 mm and 100 mm

The non-linear diametral expansions at a core diameter of 50 mm at the beginning of phase 2 are clearly higher than those of the cores with a diameter of 100 mm. Only the longitudinal non-linear expansion rates are comparable (Figure 4b). The linear expansion rates of the 50 mm cores level off in comparison to those of the 100 mm cores: the diametral expansions of the 50 mm cores increase clearly less than those of the 100mm cores. The longitudinal expansions stay constant at 0.4 mm/m (Figure 6b).

3.5 Comparison of the storage temperatures 20°C und 38°C

With the same sample shapes, the irreversible longitudinal expansions is 1.2 to 4 times larger and the diametral expansions 1.6 to 2.5 times larger at 38 °C than at 20 °C (Figure 7a). The linear expansion rates are comparable as well diametrically and longitudinally at both storage temperatures (Figure 7b). However, the non-linear expansion rates are clearly higher at 38 °C (diametral 2.1 - 3.5 times; longitudinal 2.3 – 3.8 times).

3.6 Anisotropy of the expansions

There is a systematic difference in the expansion rates, respectively the diametral and longitudinal expansions (Figures 3-5). The ratio of the expansion rates (calculated over the full duration of phase 2) across/along the core axis varies at 38°C from 0.9 to 2.5 for the 100 mm cores and from 1.7 to 3.7 for the 50 mm cores. The ratio is even higher for the 50mm cores at 20°C with values of 2.3 to 4.5. For the non-linear expansion rates at 38°C the ratios diametral/longitudinal range from 1.3 to 2.7 for the 100mm cores and from 2.9 to 4.4 for the 50mm cores. The highest ratios were measured again on the 50 mm cores at 20°C, namely from 2.8 to 6.1 (Figure 8a).

The anisotropy remains for the entire duration of the storage. The ratios diametral/longitudinal of the non-linear expansion rates are comparable with the ratio of the irreversible expansions at the end of the test with a few exceptions. The anisotropy increases with the slimmer sample shape ($D = 50$ mm) and the lower storage temperature (Figure 8a). The ratio of diametral/longitudinal expansions are always higher than 1, but the anisotropy seems to decrease with the increasing non linear expansion rates (Figure 8b).

3.7 Comparison with the field concrete

The irreversible expansions of the reactive concretes correlate well with the expansion of the prisms of the reproduced field concretes after 5 months of the concrete performance test (Figure 9a [13]). The longitudinal expansions of the 100 mm cores were used for the comparison as only longitudinal expansions are measured in the concrete performance test. The higher storage temperature of 60 °C instead of 38 °C leads to up to 2.5 times greater expansions.

The expansions measured so far on the 30 to 40 year old buildings (crack indices) are clearly larger than the irreversible expansion that could be measured in the laboratory (Figure 9b). Only structure MB differs clearly from the other concretes.

3.8 Influence of the alkali content of the concrete

The water soluble and the acid soluble alkali contents of the samples were measured before the storage (method described in [6]). Usually, the acid soluble alkali content of most Swiss field concretes is between 0.1 and 0.2 mass % $\text{Na}_2\text{O}_{\text{eq}}$, concretes with aggregates containing micas and feldspar can reach up to 0.4 mass% $\text{Na}_2\text{O}_{\text{eq}}$. The non-linear expansion rates at the beginning of phase 2 are less affected by the alkali content of the concretes while the linear expansion rates are more affected (Figure 10).

The analysis of the alkali contents at the end of the tests (335 days) showed no changes of the water and acid soluble alkali contents for 100 mm cores from the structure GU with the non-reactive aggregate. However, the analysis of samples from structure MB after 492 days of storage showed a decrease of 0.09

mass-% acid soluble $\text{Na}_2\text{O}_{\text{eq}}$ and of 0.03 mass-% water soluble $\text{Na}_2\text{O}_{\text{eq}}$ for the 100 mm cores. The decrease of the 50 mm cores was greater with 0.17 mass-% acid soluble $\text{Na}_2\text{O}_{\text{eq}}$ and 0.07 water soluble mass-% $\text{Na}_2\text{O}_{\text{eq}}$.

4 DISCUSSION

The results show that the first phase 1 of the water saturation is connected to a swelling of the sample that is not completely reversible. It is possible that the reversible hygroscopic swelling in this phase is overlapped by a swelling of already present gel in the reactive concretes (see introduction). The drying to the initial mass of the concrete allows the measurement of this irreversible part of the swelling.

The following phase 2 is divided in a phase of strong non-linear expansion followed by a stable state with a minor linear expansion. In contrast to the laboratory concrete that show an s-shaped expansion curve (concrete performance tests) the on-site concrete lacks an induction period (period until the alkali reaction leads to expansions). The characteristic expansion [8] starts immediately and reaches a concrete specific extent (duration and size of the expansion) that corresponds probably to the actual gel formation. The extent of this expansion is independent from the previous swelling during the conditioning of phase 1 but depends on the storage temperature and is larger at 38°C than at 20°C. The temperature determines the following expansion development. The higher the non-linear characteristic expansion rate at the beginning of the storage, the higher is the following linear expansion rate.

In this later part of phase 2 (stable state) the samples continuously expand and the expansion rates at 20°C and 38°C are comparable. This could indicate that the non-linear expansion is a measure for the amount of gel formed and that the following linear expansion could be interpreted as a swelling of the formed gel due to moisture uptake. The more gel is formed, the higher is the subsequent expansion due to a swelling of the gel. A further indication that the expansion at the beginning of phase 2 has a concrete specific character and depends on the kinetics of the reaction, is the surprisingly good correlation between the residual expansion and the concrete performance test of the reproduced on-site concretes. The similar composition of the gel formed during the concrete performance test and during the residual expansion test seems to indicate the presence of similar chemical reaction processes [13].

According to the analysis of [9], the reactive concrete mixtures differ from the non-reactive concretes by a higher linear expansion rate. This is confirmed by the present observations. For concretes that show an unusually high linear expansion rate in relation to their non-linear expansion rate, it can be assumed that the reaction is further enhanced by an internal alkali source ([16], e.g. structure MB). The levelling of the expansions of the 50mm cores in comparison to the larger cores also indicates that the reaction stops more rapidly due to a lack of sufficient amount of alkalis [4].

The comparison to the expansion reached so far on the structures shows that the residual expansion determined in a laboratory depends on the developed extent of the reaction and the available alkalis. Some of the expansions, for instance the expansion rates of the more damaged concrete samples are higher than those of the less damaged concrete samples. However, the expansions measured in laboratory are all in all minor compared to those approximately measured on the structures (crack index). Even if for the studied field structures a correlation between the crack index and the residual expansions seems to be present, the exceptional expansion of the samples of structure MB indicate, that a lot of uncertainties about the crack index or the residual expansion measurements still exist. Further research is needed to allow a better assessment of the expansion rates on the structures by the expansion rates observed in laboratory. But probably a final extent of the expansions cannot be determined using the laboratory samples since their expansion potential is obviously reduced by leaching of alkalis during the test.

The anisotropy of the expansion stays constant during the different phases of the storage test. This fact has been observed and discussed in various studies [11, 12, 14]. The anisotropy seems to depend on sample shape (diameter, slenderness) but also on the testing conditions. Within a given test arrangement, the ratio of the diametral and longitudinal expansions are constant. Accordingly, constant expansion ratios of 1.3-2.8 with high correlation coefficients are found by [8] at a temperature of 38 and 23 °C. The phase of the linear expansions is reached simultaneously diametrically and longitudinally. Multon [7] observed ratios of 1.4, 1.9 and 2.2 depending on the storage (100% RH, water storage, aluminium packaging).

In the present study the longitudinal expansion (meaning perpendicular to the filling direction) seem to be only little influenced by the shape of the sample (diameter, slenderness) while the diametral expansion rates (parallel to the filling direction) clearly depend on the diameter of the core (as well of the storage temperature). For 100 mm cores, the anisotropy seems to decrease with increasing expansion rates. It has been supposed [8, 17, 18] that an anisotropy in the microstructure due to segregation and a preferred orientation of flaky aggregates could be the reason for the anisotropy of the expansion. In the on-site concrete studied, there were flaky and non-flaky aggregates present depending on the specific structure, but the anisotropy was always in the same range (Figure 8a). Consequently, the effect of flaky grains and filling direction on the anisotropy cannot be confirmed.

5 CONCLUSIONS

The investigation of the residual expansion measurements on samples from different structures, with different sizes stored at different temperatures leads to the following conclusions:

The expansions during the water saturation of the samples are partially irreversible and cannot be neglected for the evaluation of the residual expansion potential.

The non-linear expansion (rate and duration) after the water saturation and at the beginning of the storage is specific for each concrete and depends on the temperature condition. It influences the following linear expansion rates, respectively the irreversible expansion reached at the end of the test. Additionally, it correlates with the expansion obtained in the concrete performance tests.

The following linear expansion rate of the samples is independent of temperature and sample diameter, but it levels off rapidly for small samples. High linear expansion rates indicate the presence of an internal source of alkalis in the concrete.

The anisotropy of the expansions stays constant during the entire test and depends on the diameter of the samples and on the storage temperature. Cores with 100 mm diameter show that the anisotropy of the expansions decreases with increasing non linear expansion rates of the concrete.

The results indicate that the expansion rates reached in the laboratory can be used for the assessment of the residual expansion potential of a concrete structure as they are specific for a given concrete. Systematic research improving the data base is needed. However, final expansion value cannot be determined because the reaction potential of the samples is exhausted after a relatively short period possibly due to alkali leaching.

From a technical point of view, the use of large and thick samples is recommended because of the reduced effect of anisotropy and of alkali loss.

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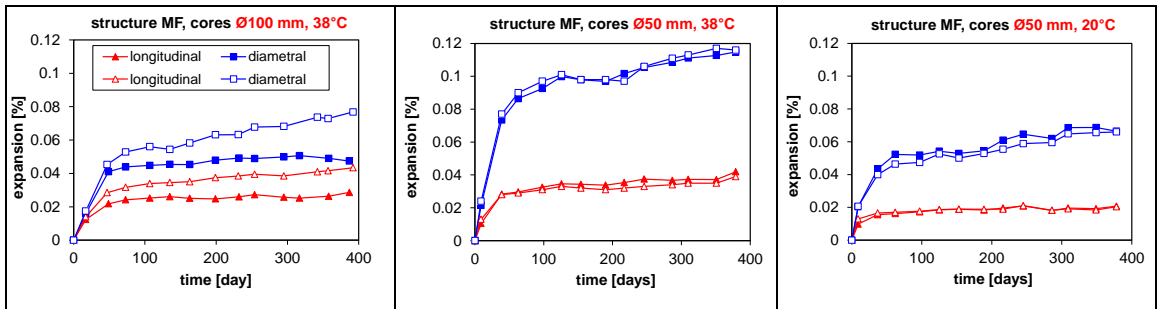


FIGURE 1: Example of residual expansions measurements on cores taken from the same structural element, but with different diameters and measured at different temperatures. Which one of the expansions measured is the right one?

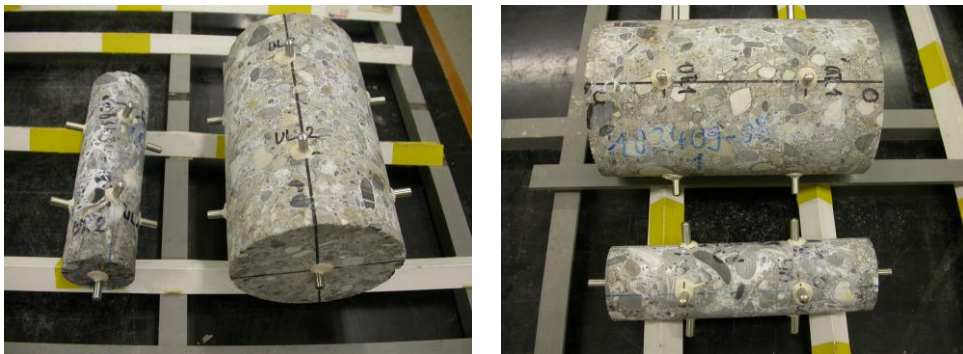


FIGURE 2: The diametral expansion has been measured crosswise at two positions on the length axis of the cores. The longitudinal expansion has been measured on the length axis between two spindles situated on the parallel end faces of the cores. Metallic spindles are fixed with glue in boreholes.

TABLE 1: Location, type and abbreviated name of the investigated structures with a simplified petrography of the aggregates (n.a. = not analysed, aggregate \varnothing_{\max} = maximum grain size used in structure).					
location, type of structure, year of construction	cement content [kg/m ³]	w/c	aggr. \varnothing_{\max} [mm]	label of aggr. and structure	present rock types (in order of decreasing amount)
Wangen, viaduct, 1977	325-350	0.45-0.50	32	GU	sandstone, quartzite, gneiss, siliceous limestone, limestone
Thielle, supporting wall, 1970/77	350-400	0.43-0.45	22	MA	limestone, limestone with detritic quartz, gneiss, sandstone, siliceous limestone, quartzite
Mattsand, dam, 1963	400	0.45-0.50	60	MS	gneiss
Ganter, bridge, 1980	400	0.40-0.45	16	MB	gneiss, schists, amphibolites, quartzites
Bornisses, supporting wall, 1967-68	400	0.45-0.50	32	VI	limestone with detritic quartz, siliceous limestone, gneiss, quartz, limestone, schist
Rorbach, bridge, 1982-83	350-400	0.45-0.50	20	UR	gneiss, siliceous limestone, sandstone, schist, limestone with detritic quartz, quartzite
Mels, viaduct, 1969	300-350	0.45	20	MF	limestone with detritic quartz, sandstone, gneiss, quartzite, schist, granophyr
Mur 10, supporting wall, 1980	400	0.43-0.45	32	ME	limestone with detritic quartz, siliceous limestone, limestone, sandstone, gneiss, quartzite, silix

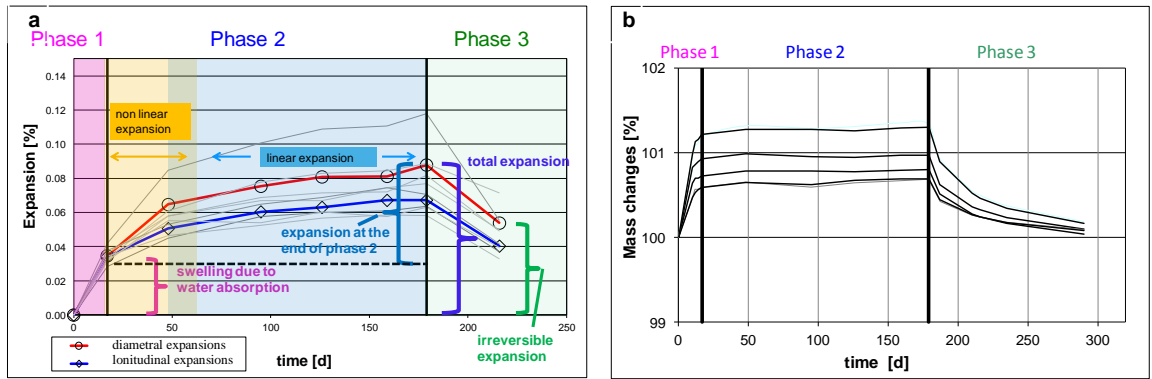


FIGURE 3: Different phases of expansion (a) and mass changes (b) during the residual expansion measurements (a: the light grey lines shows single values, the dark lines mean values).

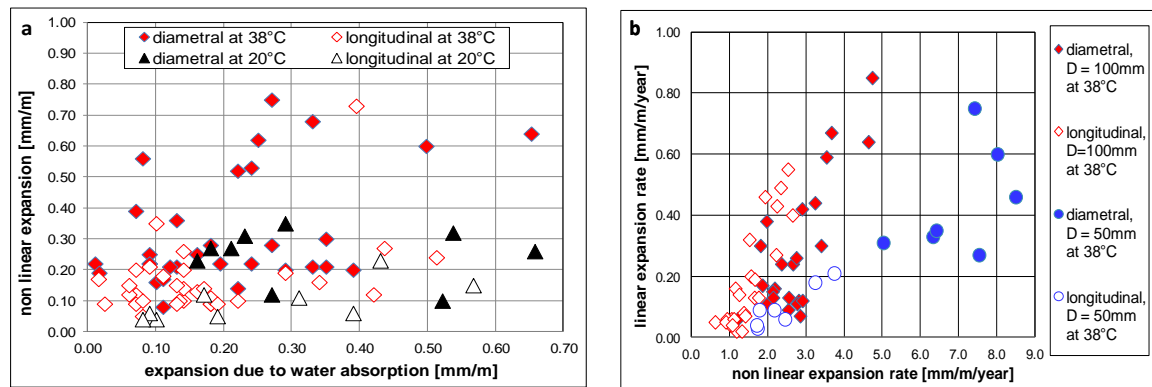


FIGURE 4a: non linear expansion at the beginning of phase 2 as a function of the expansion due to swelling during conditioning of the samples (phase 1). 4b: correlation between the non linear expansion rate at the beginning of phase 2 and the following linear expansion rate (storage at 38°C).

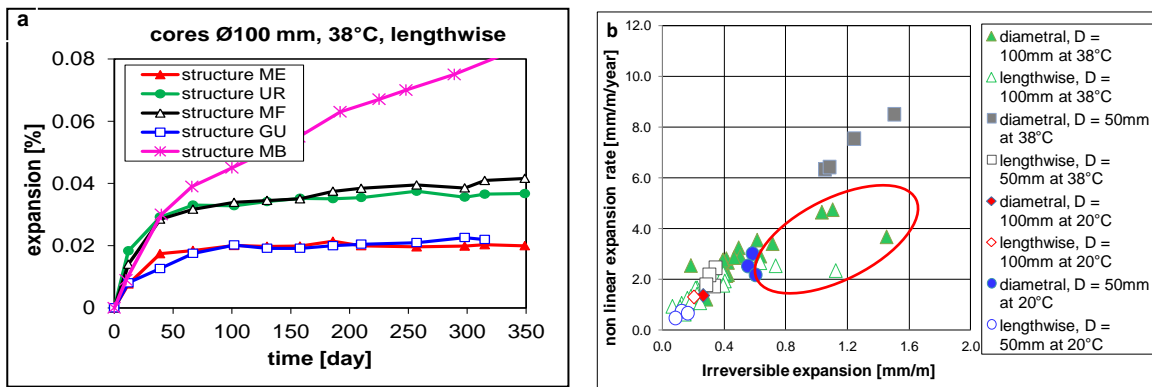


FIGURE 5a: Expansion curves (average longitudinal measures, storage at 38 °C) of field concrete, without phase 3 (drying). 5b: Irreversible expansion in function of the non linear expansion rate at 20°C and 38°C and various samples shapes. Red circle: samples of structure MB.

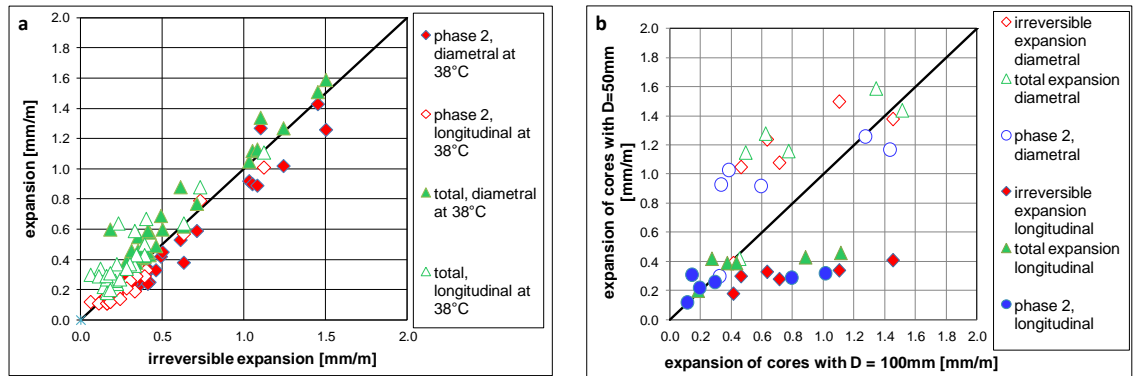


FIGURE 6a: Irreversible expansion at the end of phase 3 in function of the total expansion, the expansion during phase 2 (linear and non linear). 6b: Comparison of the expansion of cores with 50mm and 100mm diameter at 38°C.

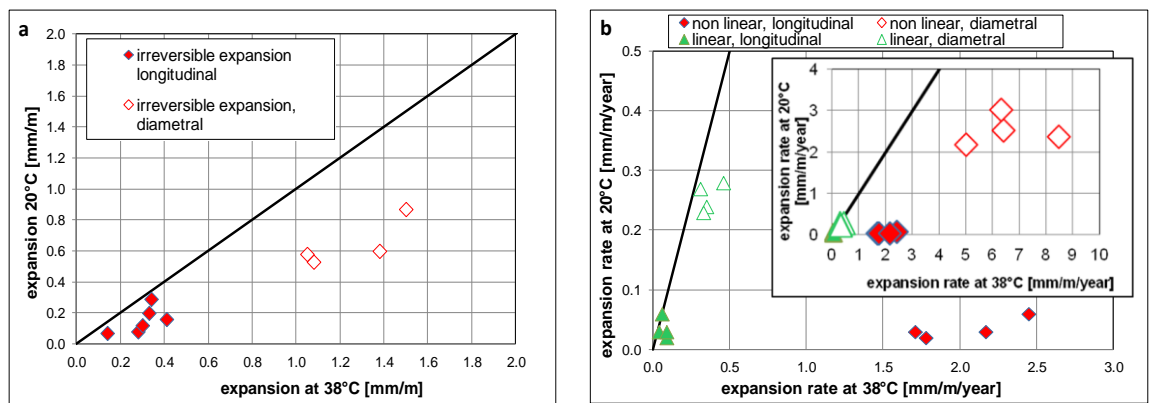


FIGURE 7: Comparison of the expansion values (a) and the expansion rates (b) at 20°C and 38°C storage temperature for cores with 50mm diameter.

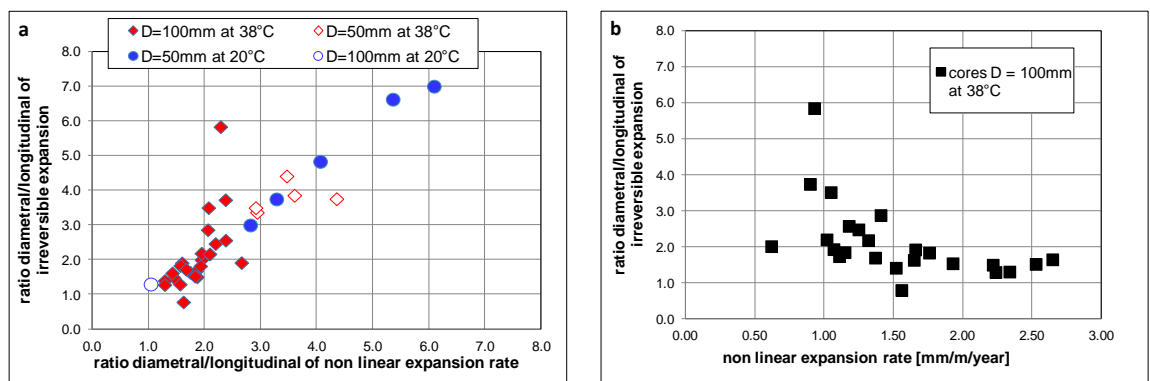


FIGURE 8a: Ratios diametral/longitudinal of the non linear expansion rates at the beginning of phase 2 at 20°C and 38°C storage temperature and for 50mm and 100mm sample diameter. 8b: ratio diametral/longitudinal of irreversible expansion as a function of the longitudinal non linear expansion rate at the beginning of phase 2.

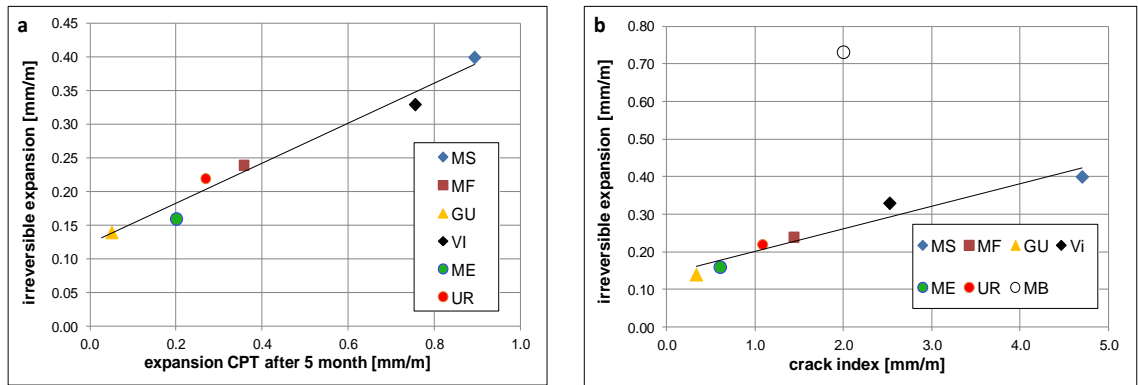


FIGURE 9: Comparison of the irreversible expansion (longitudinal, samples with $D = 100\text{mm}$ at 38°C storage temperature) with the expansion reached at the end of the concrete performance test of the field concrete reproduced in the laboratory (a) and with the crack index measured on the structure (b).

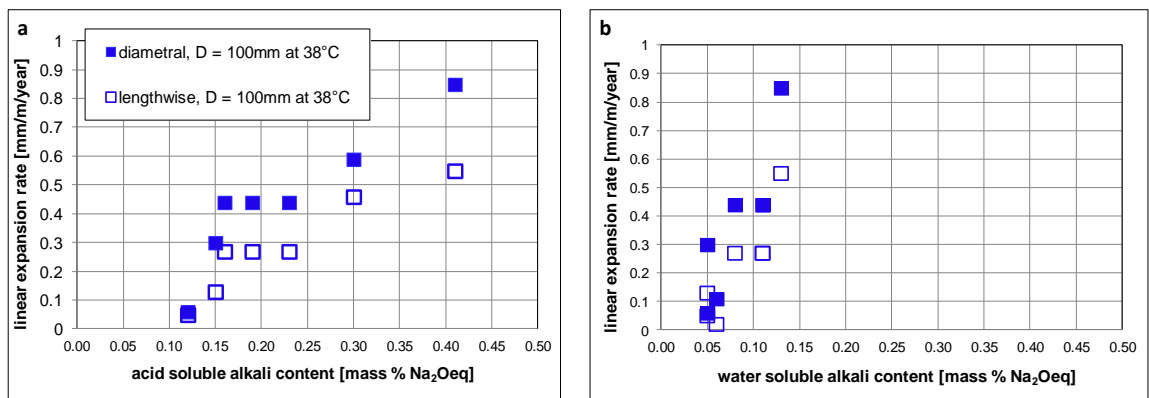


FIGURE 10: Linear expansion rate of cores with 100mm diameter at 38°C storage temperature in function of acid and water soluble alkali content of the concretes (the highest values correspond to structure MB, see also Figure 5 and 9b).