INFLUENCE OF STRESS RESTRAINT ON THE EXPANSIVE BEHAVIOUR OF CONCRETE AFFECTED BY ASR

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Abstract

The primary objective of this study was to ascertain whether the Threshold Alkali Level (TAL) of the aggregates may be taken as a suitable reactivity parameter for the selection of aggregates susceptible of alkali-silica reaction (ASR), even when ASR expansion in concrete develops under restrained conditions. Concrete mixes made with different alkali contents and two natural siliceous aggregates with very different TAL were tested for their expansivity at 38°C and 100% RH under free and restrained conditions. Four stress levels over the range from 0.17 to 3.50 N/mm² were applied by using a new appositely designed experimental equipment. The lowest stress (0.17 N/mm²) was selected in order to estimate the expansive pressure developed by the ASR gel under free expansion conditions. It was found that, even under restrained conditions, the threshold alkali level, TAL, proves to be a suitable reactivity parameter for designing concrete mixes that are not susceptible of deleterious ASR expansion. An empirical relationship between expansive pressure, concrete alkali content and aggregate TAL was developed in view of its possible use for ASR diagnosis and/or safety evaluation of concrete structures.

KEYWORDS: free expansion, restrained expansion, gel expansive pressure, threshold alkali level

1 INTRODUCTION

It is generally recognised that, for concretes containing aggregate susceptible of alkali-silica reaction (ASR) without pessimum effect, expansion behaviour is essentially related to the reactivity level of the aggregates, the alkali content of the concrete mix, the relative humidity and temperature of the environment, and the state of stress of the concrete structure.

In the absence of constraint and/or external stress, the expansion of ASR-affected concrete is commonly higher for more reactive aggregates and also increases with increasing alkali content of concrete. Previous work [1,2] has shown that, under free expansion conditions, the Threshold Alkali Level (TAL) of the aggregates represents a suitable reactivity parameter for predicting the ASR expansive behaviour of concrete under different environmental exposure conditions and varying concrete alkali content. The TAL is defined as the alkali content of concrete below which no deleterious expansion is developed by the aggregate considered.

However, recent studies have shown that the expansive behaviour of concrete is strongly dependent on the type and amount of constraint or mechanical stress applied [3]. Under restrained conditions, the expansive pressure developed by the ASR gel would not always be proportional to free expansion, especially in the case of relatively high alkali contents of concrete, where very low expansive pressures may result in contrast to high free expansivities. The practical inference of the findings [3] is that the suitability of the conventional concrete prism expansion tests (based on free expansion) for ASR assessment in concrete structures, as well as the validity of the reactivity parameter TAL, as determined from such conventional tests, could be strongly questioned.

Therefore, the present study was undertaken to accomplish the following two objectives: 1) to ascertain the suitability of the threshold alkali level as a reactivity parameter under constraint conditions that are typical of concrete dams, and 2) to develop an empirical relationship between expansive pressure, concrete alkali content, and aggregate TAL, in view of a possible use of such a relationship for ASR diagnosis and/or safety evaluation of existing concrete structures.

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2 MATERIALS AND METHODS

2.1 Materials and mix designs

Two natural ASR-susceptible aggregates of known field performance, designated by letters A and B, were tested in this study. These aggregates came from Italian quarries and were available both as coarse and as fine aggregate.

As evidenced by the RILEM AAR-1 petrographical examination [4], aggregate A was composed primarily of fine grained carbonate rocks (80%), isolated microfossils, fine grained flint (5%), mono- and poly-crystalline quartz (3%) with high undulatory extinction angle, sandstone, feldspar and opaque minerals. Aggregate B primarily consisted of mono- and poly- crystalline quartz and quartzite (>80%) with low undulatory extinction, gneiss and micaschists, serpentine, amphibole rocks, feldspars, micas, garnets, epidotes and opaque minerals. The TAL values of aggregates A and B were, respectively, 4.4 and 7.0 kg Na_2Oeq/m^3 when determined at 38°C and 100% relative humidity (RH) using a modified version of the RILEM AAR-3 concrete prism test [5]. The only modification of the standard test procedure [6] consisted of varying the alkali content of the concrete mix.

Concrete mixes for free and restrained expansion tests were prepared using both the fine and coarse test aggregate, a low-alkali Portland cement (CEM I 42.5; Na_2Oeq = 0.59%; MgO =1.20%; Blaine specific surface area = 400 m^2/kg), and deionised water as mixing water. The grading of the combined aggregate (0-20 mm) and the concrete mix proportions (free water to cement weight ratio = 0.455; coarse aggregate: fine aggregate: cement = 2.83: 1.22: 1 by mass; cement content = 440 kg/m^3) were the same as those specified in the RILEM AAR-3 concrete prism test [6].

Different alkali contents (Lac) of the mixes were considered: 5.5, 6.5, and 7.5 kg Na_2Oeq/m^3 for aggregate A (TAL= 4.4 Na_2Oeq/m^3) and 6.5, 7.5, and 8.5 kg Na_2Oeq/m^3 for aggregate B (TAL= 7.0 kg Na_2Oeq/m^3). These alkali contents were obtained through appropriate additions of reagent-grade NaOH pellets to mixing water.

2.2 Methods for assessment and analysis

Casting and curing

From each concrete mix, 75 × 75 × 250 mm test prisms were cast and stored under moist covers for 24 h at 20°C and relative humidity of not less than 90%. After demoulding, the concrete specimens were initially cured for 7 days at 20°C and 90% RH, and then subjected to restrained and free expansion tests at 38°C and 100% RH. In particular, for each mix, three specimens were put into the AAR-3 RILEM containers for free expansion tests and other twelve specimens were subjected to restrained expansion tests (three for each of the four stress levels considered) by using newly designed equipment, as described in the following section.

Test method to evaluate the influence of stress restraint on specimen expansion

Because a standard test method for evaluating the influence of mechanical stress on the ASR expansive phenomena does not still exist, a new appositely designed experimental equipment has been set up. It consisted of a pressure cell (Figure 1) suitably conceived in order to apply sustained axial compressive stresses on a concrete specimen of the same size as that specified in the RILEM AAR-3 and under the same temperature and relative humidity conditions (38°C and 100% RH).

The adopted testing device, based on that proposed for mortar specimens by Kawamura & Iwahori [3], was composed of two main steel plates connected by four threaded steel bars. A load cell, acting as a calibrated spring, was interposed between the concrete specimen and the top steel plate. The environmental conditions were assured by filling the bottom basin of the cell with water and by using a lattice membrane enclosing the cell itself.

The mechanical stresses were applied locking the bolts of the threaded steel bars at the beginning of the test and never removed. Four stress levels (σ_c) were tested: 0.17, 0.87, 2.18 and 3.50 N/mm^2. These low compressive stresses are typical of concrete dams. During the test, stress increased due to expansive pressure developed by ASR gel. The lowest initial stress condition (0.17 N/mm^2), simulating the case of a restraint with no practical stress, was selected in order to evaluate the expansive pressure developed by the ASR gel under "free" expansion conditions.

Expansion and expansive pressure measurements

For all concrete specimens investigated, length changes were measured in longitudinal (E_{lon}%) and transversal (E_{tra}%) directions over 200 and 50 mm length and width respectively as shown in Figure 1. For the prisms without constraint, the axial measurement (E_{ax}%) was also performed according to RILEM AAR-3 test method.

Longitudinal expansions were evaluated on each one of the four prism sides, while transversal expansions were measured on two opposite sides of the same specimen, in the middle of the specimen length. The averages of these measures were taken as the longitudinal and transversal expansions of each specimen at a given curing time. In the case of restrained expansion tests, length measurements were made on loaded specimens, at the same curing times as that of free specimens.

Before each length measurement, the free concrete specimens and the pressure cells with restrained concrete specimens were removed from the testing environment (38°C and 100% RH) and equilibrated at 20°C and 65% RH. The measurements of length changes were made manually using an analogue gauge. For restrained concrete specimens, length measurements were made by keeping the specimens under loaded conditions in the pressure cells. No thermal correction was done, as measurements were always performed at the same temperature (20°C) and the same thermal linear expansion coefficient was assumed for concrete and steel. The total stresses (initial restraining stress + ASR expansive pressure) acting on the specimens were continuously monitored throughout the test, by using a storage acquisition system. Thus it was possible to obtain the expansive pressure developed by the ASR gel under "free" expansion conditions (specimens subjected to the lowest stress σ_c = 0.17 N/mm^2). The percent linear expansion of the prisms at a given curing time was calculated as the average expansion of three specimens. The coefficient of variation for expansion measurements within a set of specimens was always less than 7% for average percent expansions greater than 0.10%.

3 RESULTS

For restrained specimens, longitudinal and transversal expansions were adjusted taking into account the elastic deformation in order to consider only the effective strain caused by the ASR gel pressure. The strain elastic components were estimated on the basis of the values of the static elastic modulus experimentally determined on the two concretes at the age of the specimen loading (E=23370 N/mm^2 for the concrete made with aggregate A; E=25960 N/mm^2 for the concrete with aggregate B) and assuming a Poisson coefficient value of 0.20. Creep deformations were instead disregarded, mainly because of the extremely low compressive stress levels considered in the experiments (0.87-3.50 N/mm^2).

Due to space restraints to the present manuscript, the curves showing the development of longitudinal and transversal expansions as a function of curing time are not here reported for each of the concrete mixes investigated. A representative example is only provided by Figure 2, where the longitudinal free and restrained (at four stress levels) mean expansions are plotted against time up to one year of curing, in the case of concrete mixes made with aggregates A and B and an alkali content of 7.5 kg Na_2Oeq/m^3 (common to both aggregates).

Figure 3 shows the expansive pressure developed by the ASR gel under a minimum restraint of 0.17 N/mm^2 plotted against time for all the concrete mixes investigated. For both aggregates, the expansive pressure increases as the concrete alkali content is increased. As expected, at the same alkali content, concrete mixes with more reactive aggregate (A) develop higher pressures. At the highest alkali level pressure values up about 6.0 N/mm^2 were measured.

Figure 4 shows the values of all free expansive parameters (E_{ax}, E_{lon}, E_{tra}) at 365 days of curing plotted against concrete alkali content. With reference to axial expansion, E_{ax}%, (on unrestrained prisms according to RILEM AAR-3 [6]), except for the concrete mix with aggregate B at the lowest alkali content (6.5 kg Na_2Oeq/m^3), the expansion always exceeds the limit of 0.05% suggested by RILEM AAR-0 [7]. Longitudinal free expansions, E_{lon}% (on restrained prisms as shown in Figure 1) are consistent with free axial expansions. Strains are generally a little bit higher in the longitudinal direction than in the transversal one, showing a practical isotropic behaviour of the free expansive phenomenon. For both aggregates, no pessimum effect is observed, since the expansivity always increases with increasing alkali content of concrete mix. Moreover, the TAL values obtained in a previous study [5] were confirmed, proving the greater reactivity of aggregate A as compared to B.

In Figures 5 and 6, 365-day expansions of specimens in both longitudinal and transversal directions are shown plotted against compressive stress, σ_c. At a fixed concrete alkali level, longitudinal restrained expansions are always lower than longitudinal free expansions, and the former also decrease with increasing compressive stress. Transversal expansions are generally greater than the corresponding longitudinal ones, particularly at high stress levels, showing an anisotropic behaviour of the expansive phenomenon under restrained conditions.

Assuming that, over the range of investigated stress, the ASR expansive pressure is not affected by the compressive stress applied, it is possible to estimate the expansive pressure, P_g, developed by ASR gel at each alkali content by using the curves in Figures 5 and 6. In particular, the values of P_g may be obtained as interception of the restrained longitudinal expansion curves with the abscissa axis. These expansive pressures (2.2, 3.5 and 5.0 N/mm^2 for aggregate A and 0.7, 1.3 and 2.5 N/mm^2 for aggregate B) are in good agreement with those determined experimentally under test conditions approaching free expansion (Figure 3).

4 DISCUSSION

The effect of increasing the stress applied to the concrete specimen is clearly highlighted by the decrease of their longitudinal expansion that gradually vanishes as the applied stress is increased (Figure 2). No longitudinal expansion was already observed at σ_c = 0.87 N/mm^2 for the less reactive aggregate (B) and at σ_c = 2.18 N/mm^2 for the more reactive aggregate (A).

Figure 7 compares the 365-day axial free expansions (Figure 4) and the corresponding expansive pressures determined experimentally on all concrete mixes investigated (Figure 3). In this figure, the results of a previous study by Kawamura and Iwahori [3] on mortar specimens are also reported. The experimental data of the present study show a linear relationship between expansive pressure and free expansion and, at least up to an expansive pressure of about 3 N/mm^2, also the data presented in [3] fit such a relationship except for the two points at the upper left corner of the plot.

As evidenced by the comparison between the "free" expansive pressures determined experimentally (Figure 3) and those estimated from restrained expansion data (Figures 5 and 6), the expansive pressure developed by the ASR gel, under applied compressive stresses ranging from 0.17 to 3.50 N/mm^2, appears to be virtually unaffected by some mechanical and physico-chemical phenomena induced by the application of a restraint. These phenomena include: 1) microcracking of concrete, that increases its porosity, thus reducing the expansive pressure of the ASR gel [8], and 2) slower ASR development (as compared to free expansion) with formation of a gel characterised by smaller water absorbing capacity and swelling properties and, consequently, by lower expansive pressure, in analogy to other more known expansive phenomena (e.g., expansive ettringite formation from hydration of calcium sulfo aluminate $4CaO \cdot Al_2O_3 \cdot SO_3$ in the presence of gypsum and lime) [9].

Figure 8 shows the effect of increasing the concrete alkali content on the expansive pressure, P_g, developed by ASR gel after 365 days of curing at 38°C and 100% RH. As expected, at a fixed alkali content, the expansive pressure P_g measured on the concretes made with more reactive aggregate (A) is always higher as compared to the concretes made with less reactive aggregate (B). The difference between the alkali content of concrete (L_{ac}) and the threshold alkali level (TAL) of the aggregate used may be taken as the driving force for ASR development.

Considering the linear relationship between free expansion and expansive pressure (Figure 7), it is likely to think that the driving force, L_{ac}-TAL, should be in relation with the gel expansive pressure. This is confirmed by Figure 9, where the expansive pressure, P_g, and the driving force, L_{ac}-TAL, are shown to be related by a unique exponential relationship, irrespective of the aggregate type and the concrete alkali content considered. This proves that, even under restrained conditions, the threshold alkali level, TAL, is a suitable reactivity parameter for designing concrete mixes that are not susceptible of deleterious ASR expansion.

From Figure 9 it can also be observed that, when the concrete alkali content, L_{ac}, is equal to the threshold alkali level, TAL, of the aggregate, i.e. for an axial expansion equal to 0.05% (expansion limit suggested by RILEM), the expansive pressure is 0.90 N/mm^2. For expansion levels below 0.05% (e.g., E_{ax}=0.024% for the concrete mix made with aggregate B and L_{ac}= 6.5 kg Na_2Oeq/m^3), the expansive pressure is 0.45 N/mm^2 as seen from Figure 8. The relationship of Figure 9 could also be useful to quantify, for a specific concrete composition, the parameters required for structural analysis of ASR-affected concrete structures through the use of mathematical models such as, for example, the concrete growth function proposed by Charlwood *et al.* [10], [11].

In order to take into account the dependence of the ASR gel expansion within a concrete structure on its stress state, the model developed by the above Authors assumes the concrete expansion under low compressive stresses as an anisotropic phenomenon and the strain growth rate, $\dot{\varepsilon}^{aar}(t)$, at each time t, is resolved to the direction of the principal stress (i) (Figure 10) as follows:

$$\dot{\varepsilon}_i^{aar} = \dot{\varepsilon}^{free} - K * Log\left(\frac{\sigma_i}{\sigma_L}\right) \tag{1}$$

where:

$\dot{\varepsilon}^{aar}$ = restrained strain growth rate in correspondence of time t (% expansion/year)
$\dot{\varepsilon}^{free}$ = free strain growth rate at the same time t (% expansion/year)
σ_i = principal stress in the direction i
σ_L = stress below which $\dot{\varepsilon}^{aar}$ is constant and equal to free expansion rate, $\dot{\varepsilon}^{free}$
K = slope of the line defining the strain growth rate versus the logarithm of stress.

The stress σ_L is generally taken equal or lower than 0.3 N/mm^2 . The constant K is calculated from Equation (1) letting $\sigma_i=\sigma_{max}$, where σ_{max} is the stress at which $\dot{\varepsilon}^{aar}=0$ (Figure 10). Thus, for a specific concrete, the value of σ_{max} required to calculate K could be obtained from the relationship of Figure 9, referring to one year of testing under accelerated conditions (38°C and 100% RH).

5 CONCLUSIONS

Under both free and restrained test conditions, the threshold alkali level, TAL, of the aggregates proves to be a suitable reactivity parameter for designing concrete mixes that are not susceptible of deleterious ASR expansion during their service life.

Over the range of applied compressive stresses (0.17-3.50 N/mm^2), that are typical of concrete structures such as concrete dams, the expansive pressure developed by the ASR gel is greatly affected by the concrete alkali content, L_{ac} (P_g significantly increases with increasing L_{ac}), while it is virtually unaffected by the stress applied.

Irrespective of the type of aggregate and alkali content of concrete considered, there exists an unique exponential relationship between the expansive pressure developed by the ASR gel and the driving force for ASR development, the latter being defined as the difference between the alkali content of concrete, L_{ac}, and the TAL of the specific aggregate used for concrete formulation.

Such a relationship may be useful to calculate key parameters in structural models developed for ASR diagnosis and/or safety evaluation of existing concrete structures.

6 ACKNOWLEDGEMENTS

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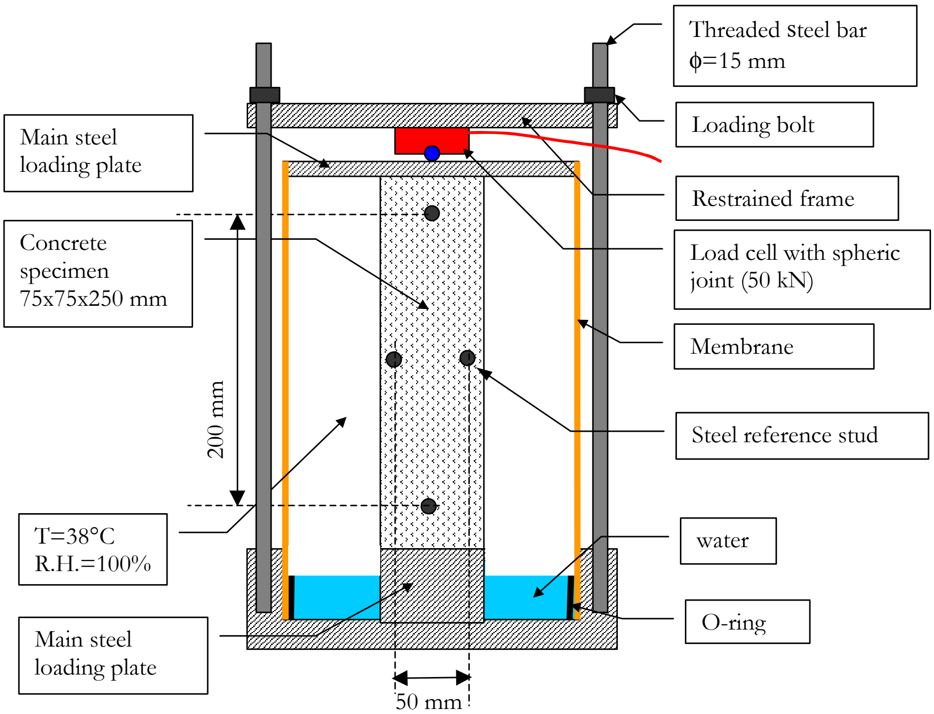

Figure 1: Schematic lay-out of the steel pressure cell for measuring expansion and expansive pressure

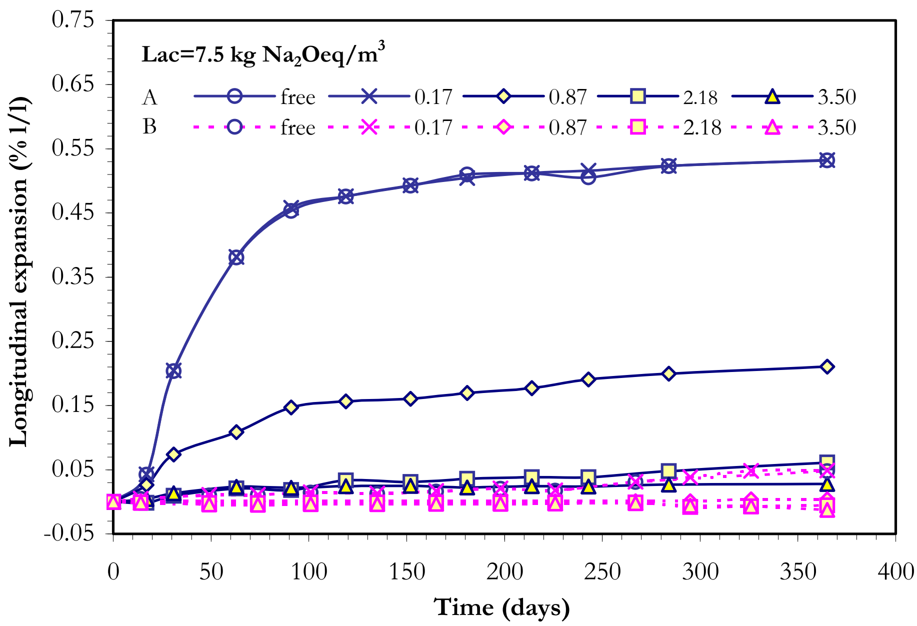

Figure 2: Length change vs. time for concrete prisms (alkali content = 7.5 kg Na_2Oeq/m^3) under different test conditions (free and restrained expansion)

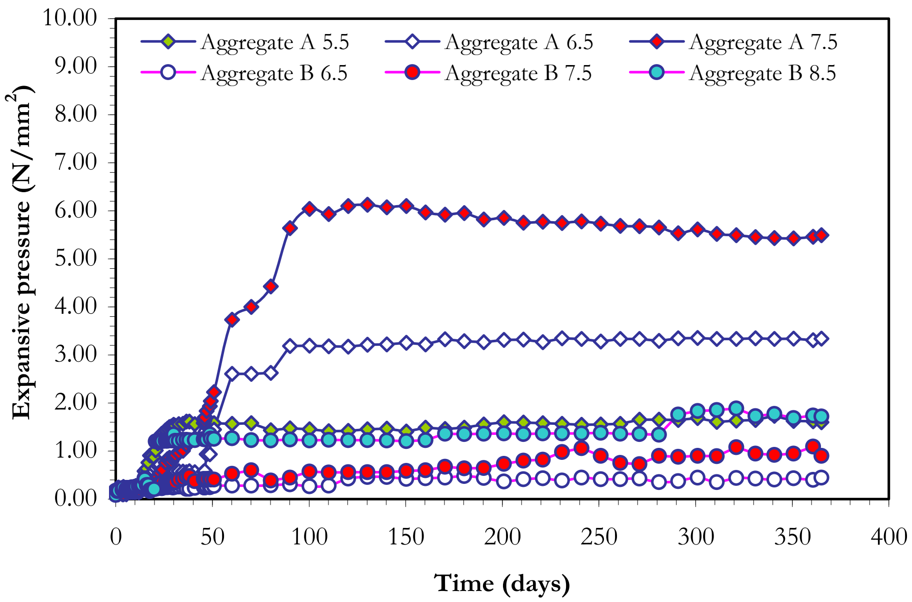

Figure 3: Development of "free" expansive pressure (under the lowest restraining stress of 0.17 N/mm²) for all concrete mixes investigated

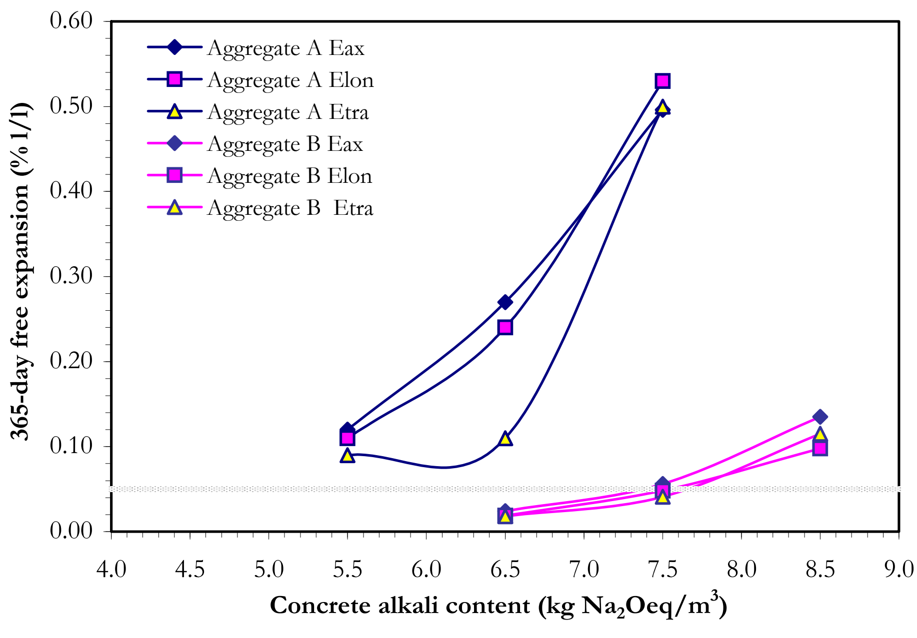

Figure 4: Ultimate free expansion (axial, longitudinal, transversal) vs. concrete alkali content

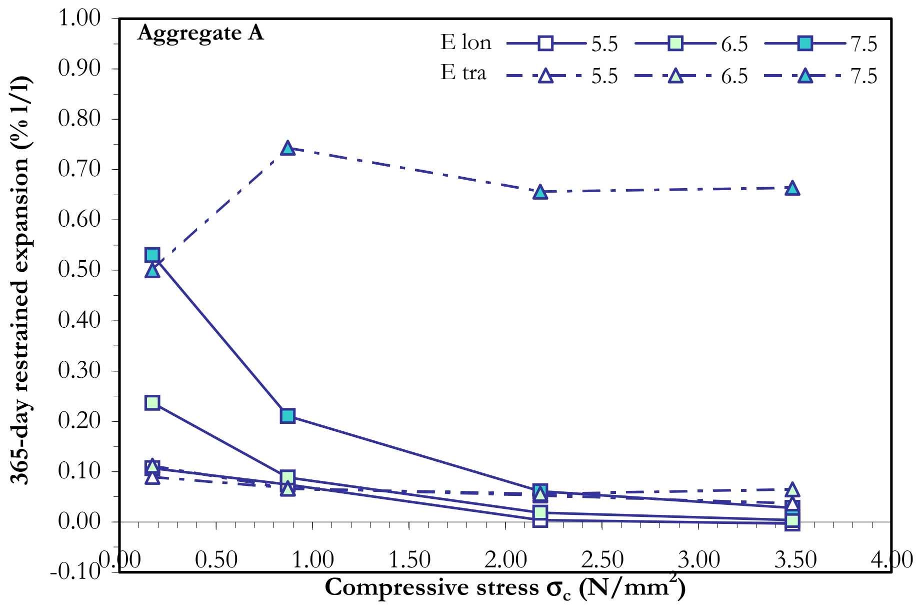

Figure 5: Ultimate restrained longitudinal expansion vs. compressive stress (aggregate A)

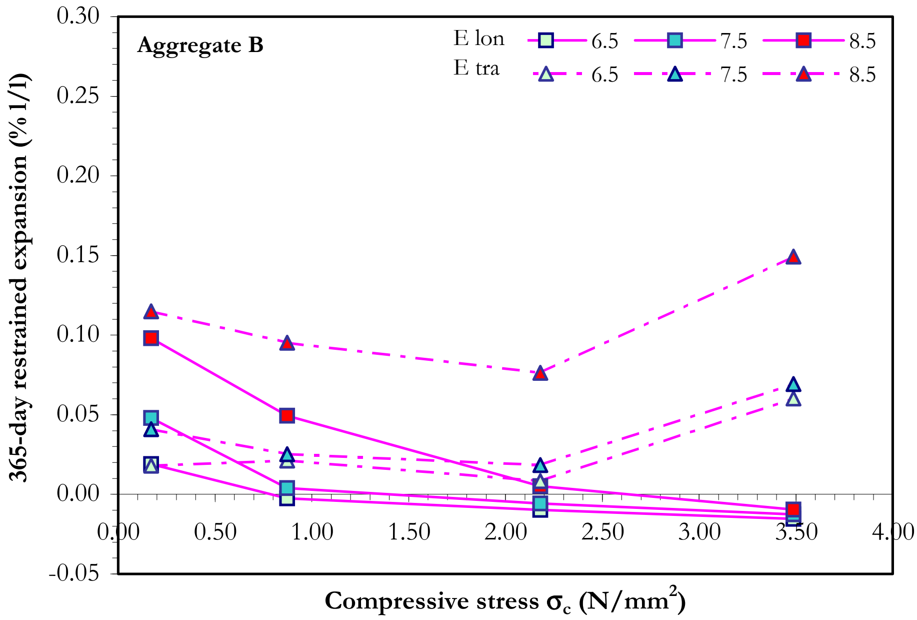

Figure 6: Ultimate restrained longitudinal expansion vs. compressive stress (aggregate B)

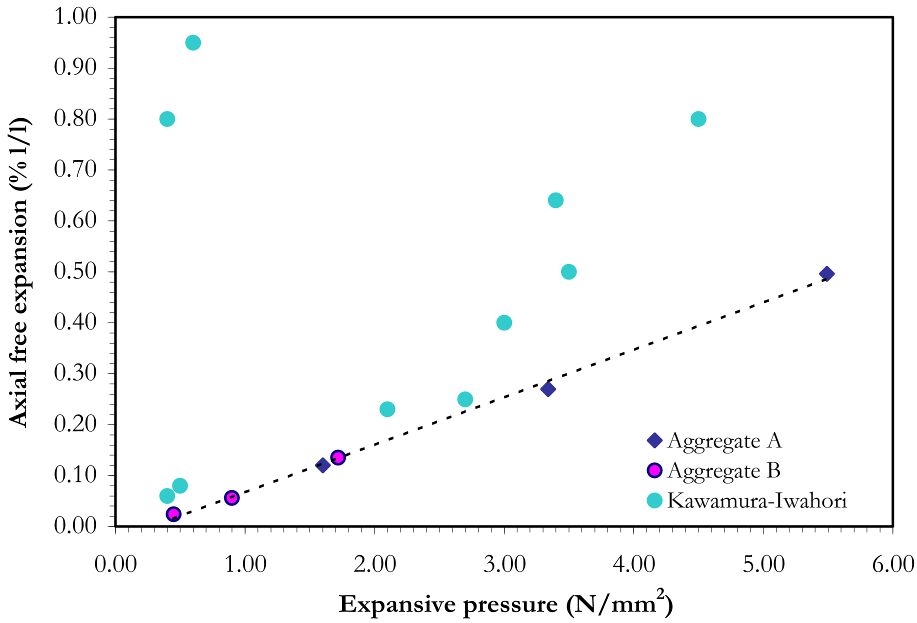

Figure 7: Axial free expansion vs. expansive pressure after one year of measurements (experimental data compared with previously published data from literature)

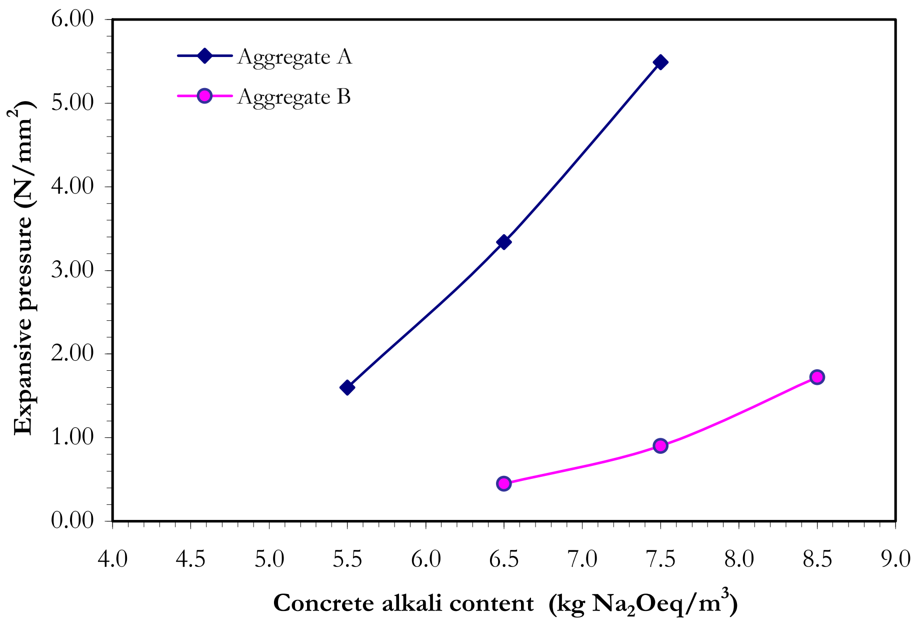

Figure 8: Expansive pressure vs. concrete alkali content after one year of measurements

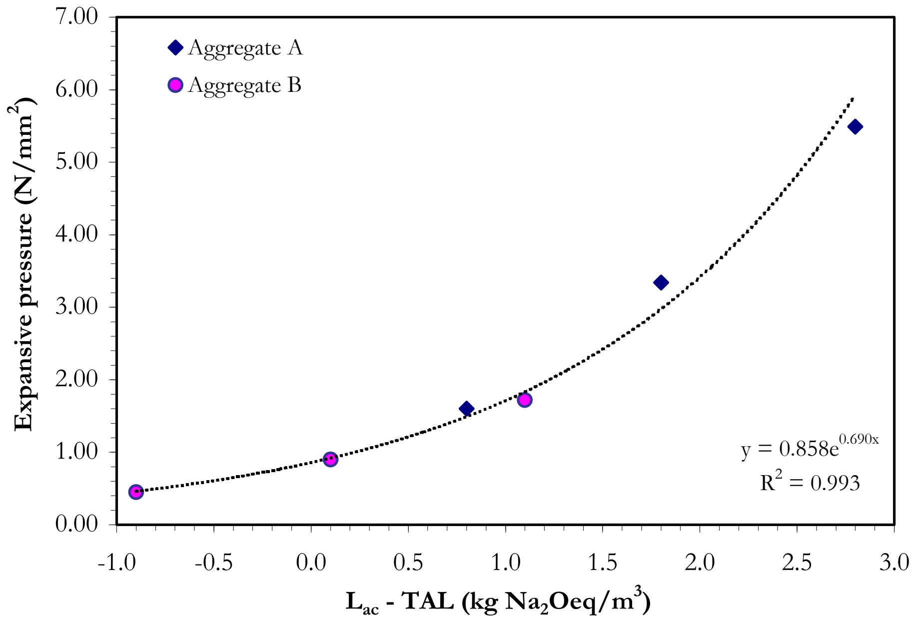

Figure 9: Expansive pressure vs. driving force for ASR development

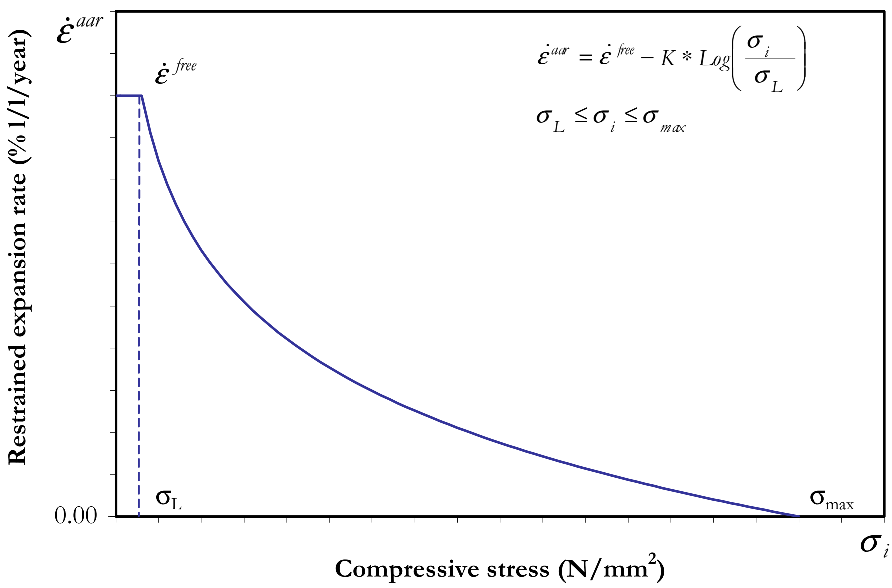

Figure 10: Relationship between concrete strain growth rate $\dot{\varepsilon}^{aar}$ and principal stress σ_i in ASR [10] [11]