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Influence of stress restraint on the expansive behaviour of concrete affected by alkali-silica reaction

M. Berra [a,*], G. Faggiani [a], T. Mangialardi [b], A.E. Paolini [b]

[a] ERSE S.p.A., Via Rubattino, 54-20134 Milano, Italy
[b] Facoltà di Ingegneria, Università "La Sapienza", Via Eudossiana, 18-00184 Roma, Italy

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ABSTRACT

The primary objective of this study was to ascertain whether the Threshold Alkali Level (TAL) of the concrete 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 TALs were tested for their expansivity at 38 °C and 100% RH under unrestrained and restrained conditions. Four compressive stress levels over the range from 0.17 to 3.50 N/mm^2 were applied by using a new appositely designed experimental equipment. The lowest stress (0.17 N/mm^2) 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 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.

1. Introduction

It is generally recognised that, for concretes containing aggregates susceptible of alkali-silica reaction (ASR) with no "pessimum" effect, the expansive 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 [1–3] has shown that, under unrestrained expansion conditions, the Threshold Alkali Level (TAL) is a characteristic alkali-reactivity property of each aggregate and it may be defined as the alkali content of the concrete mix below which no deleterious expansion is developed by the aggregate considered. For concrete mixes made with a fixed proportioning of ingredients and stored under established thermo-hygrometric conditions, the TAL value is only dependent on the alkali-reactivity of the specific aggregate: the higher is the aggregate reactivity, the lower the TAL value. Under the experimental test conditions specified in the RILEM Recommended Test Method AAR-3 [4], the expansion limit of 0.05% at 1 year [5] may be assumed as a criterion for the TAL determination.

As discussed in our previous papers [1–3], the TAL may be a suitable reactivity parameter for predicting the ASR expansive behaviour of concrete under different environmental exposure conditions and varying concrete alkali content. In particular, on the basis of the TAL of the specific aggregate to be used in a concrete structure and the extra-amounts of alkalies derived from the exposure conditions, it is possible to calculate the safe alkali content of concrete. If this safe alkali content is incompatible with the engineering properties required for the structure, then the aggregate considered has to be rejected and replaced with an aggregate having a higher TAL value. Alternatively, preventive measures such as the use of active mineral admixtures or lithium salts may be adopted to counteract the ASR development.

However, a recent study by Kawamura and Iwahori [6] has shown that the expansive behaviour of concrete is also strongly dependent on the type and amount of constraint or mechanical stress applied. Under restrained conditions, the expansive pressure developed by the ASR gel would not always be proportional to unrestrained expansion. In particular, especially in the case of relatively high alkali contents of concrete, in restrained concrete specimens very low expansive pressures may be associated to high unrestrained expansivities [6]. The practical inference of the findings is that the suitability of the conventional concrete prism expansion tests (based on unrestrained 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

* Corresponding author. Tel.: +390239925920; fax: +390239924608.
E-mail address: mario.berra@erse-web.it (M. Berra).

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alkali level as a reactivity parameter under restrained 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.

2. Materials and methods

2.1. Concrete mix design and curing

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 fractions.

As evidenced by the RILEM AAR-1 petrographical examination [7], 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 angles, gneiss and micascists, 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_2O_{eq}/m^3. They were determined using a modified version of the RILEM AAR-3 concrete prism test [2].

Concrete mixes for unrestrained and restrained expansion tests were prepared using the test aggregates (fine and coarse fractions), a low-alkali Portland cement (CEM I 42.5; Na_2O_{eq} = 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 [4]. The only modification of the RILEM standard concrete test procedure consisted in varying the alkali content (L_{ac}) of the concrete mix. The L_{ac} values were selected in order to investigate a suitable range of alkali levels above the TAL of each aggregate (reactivity conditions): 5.5, 6.5, and 7.5 kg Na_2O_{eq}/m^3 for aggregate A (TAL = 4.4 kg Na_2O_{eq}/m^3) and 7.5, and 8.5 kg Na_2O_{eq}/m^3 for aggregate B (TAL = 7.0 kg Na_2O_{eq}/m^3). For the latter aggregate, the value of 6.5 kg Na_2O_{eq}/m^3, that was slightly lower than its TAL, was also considered, with the purpose of having a checking. These alkali contents were obtained through appropriate additions of reagent-grade NaOH pellets to mixing water.

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 unrestrained expansion tests at 38 °C and 100% RH. In particular, for each mix, three specimens were put into the AAR-3 RILEM containers for unrestrained expansion tests and other twelve specimens were subjected to restrained expansion tests (three for each of the four stress levels considered) by using a new appositely designed equipment, as described in the following section.

2.2. Test methods for assessment of concrete expansive behaviour

An experimental equipment, as shown in Fig. 1, was appositely designed and set up for evaluating the influence of mechanical stress on the ASR expansive phenomena in concrete. It consisted of a pressure cell 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 and Iwahori [6], 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 100% RH condition was 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 initial compressive 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 (test duration = 365 days), stress increased due to expansive pressure developed by ASR gel, so that it was necessary to remove periodically the stress in excess, in order to perform expansion

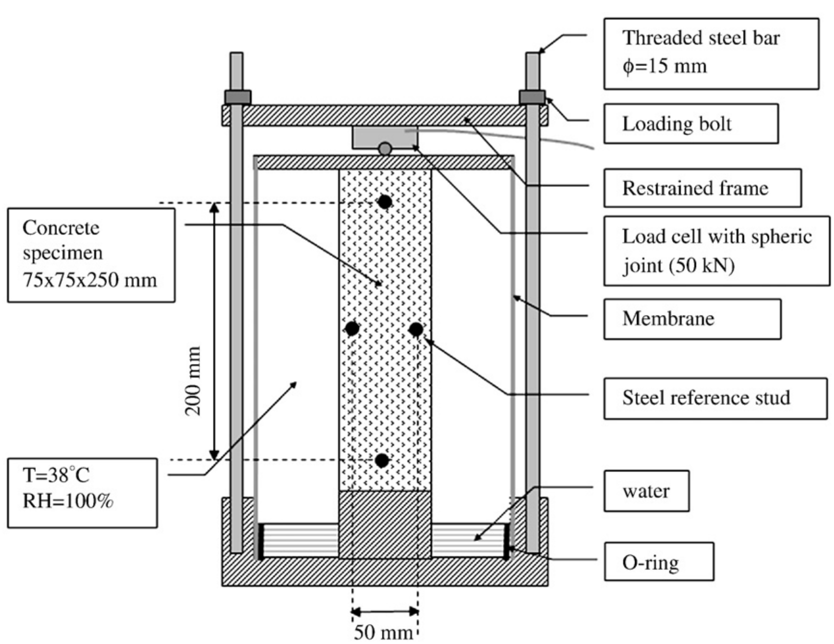

Fig. 1. Schematic lay-out of the steel pressure cell for measuring expansive pressure and expansion under restrained conditions.

tests under constant load. The total stress (initial restraining stress + ASR expansive pressure) acting on the specimens was continuously monitored throughout the test, by using a storage acquisition system. 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.

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 Fig. 1. For the unrestrained prisms, 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 unrestrained specimens.

Before each length measurement, the unrestrained specimens and the pressure cells with restrained specimens were removed from the testing environment (38 °C and 100% RH) and equilibrated at 20 °C and 65% RH. The length changes were made manually using an analogue gauge. For restrained 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 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 12%.

For the restrained specimens, the ultimate longitudinal and transversal expansions were corrected for elastic and creep deformations (purely mechanical strains), in order to consider only the effective strain caused by the ASR gel.

Purely mechanical deformations were estimated through the calculation of the viscosity function, $J(t_0, t)$, as proposed by the Eurocode 2 [8] and assuming a Poisson coefficient value of 0.20. For the calculation of the function $J(t_0, t)$, the values of the static elastic modulus (E_s) determined on the two types of concrete after 7 days of curing at 20 °C (t_0) and after 28 days of curing (7 days at 20 °C and 21 days at 38 °C and 100% RH) were used (E_{s7} = 23370 N/mm^2 and E_{s28} = 33100 N/mm^2 for the concrete made with aggregate A; E_{s7} = 25960 N/mm^2 and E_{s28} = 34800 N/mm² for the concrete with aggregate B).

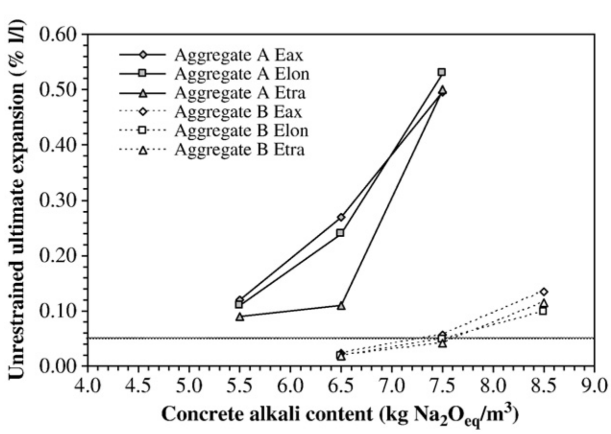

Fig. 2. Unrestrained ultimate expansion (axial, longitudinal, and transversal) vs. concrete alkali content.

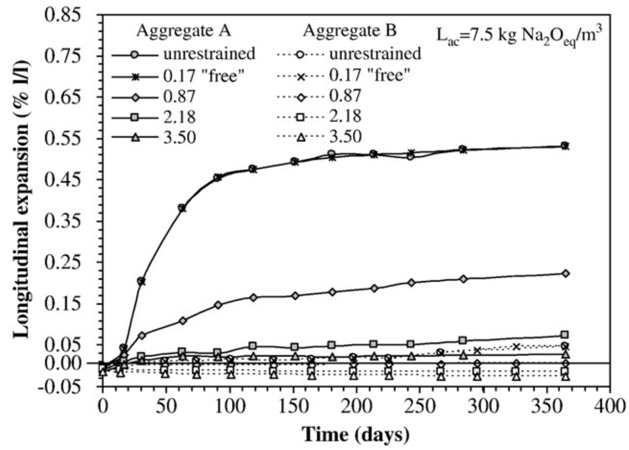

Fig. 3. Unrestrained and uncorrected restrained expansions vs. time for concrete prisms (L_{ac} = 7.5 kg Na_2O_{eq}/m^3).

3. Results and discussion

3.1. Unrestrained and restrained expansions

Fig. 2 shows the values of all unrestrained expansive parameters (E_{ax}, E_{lon}, E_{tra}) after 365 days of testing (ultimate time of expansion) plotted against concrete alkali content (L_{ac}) for all concrete mixes investigated.

It can be noted that, except for the concrete mix with aggregate B at the lowest alkali content (L_{ac} = 6.5 kg Na_2O_{eq}/m^3), the axial ultimate expansion, E_{ax}%, always exceeded the limit of 0.05% after 365 days suggested by RILEM AAR-0 [5]. Longitudinal ultimate expansions, E_{lon}%, were always consistent with ultimate axial expansions. Strains were only a little bit higher in the longitudinal direction than in the transversal one, thus indicating a practical isotropic behaviour of the expansive phenomenon under unrestrained conditions. For both aggregates, no "pessimum" effect was observed, since the expansivity always increased with increasing alkali content of concrete mix. Moreover, the TAL values obtained in a previous study [2] on the same aggregates were confirmed, further proving the greater reactivity of aggregate A as compared to B.

Fig. 3 is a representative plot showing the effect of increasing the restraining stress, σ_c, on the expansive behaviour of concrete specimens. In this figure, the unrestrained and restrained (uncorrected for mechanical strains) longitudinal expansions, E_{lon} %, of concrete mixes made with an alkali content of 7.5 kg Na_2O_{eq}/m^3 (common to both aggregates), are plotted as a function of time up to 365 days of curing.

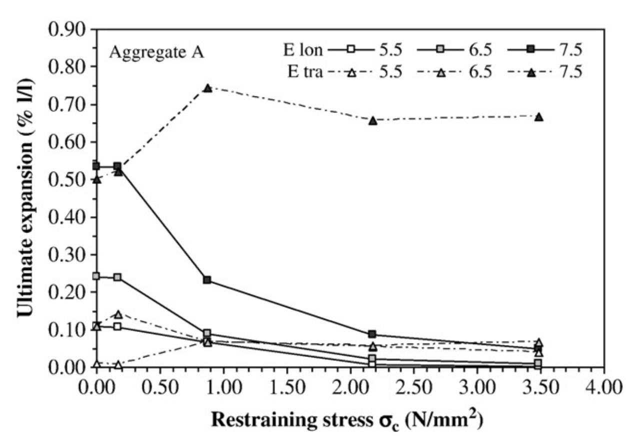

Fig. 4. Unrestrained and restrained (longitudinal and transversal) ultimate expansions vs. restraining stress for concrete mixes made with aggregate A.

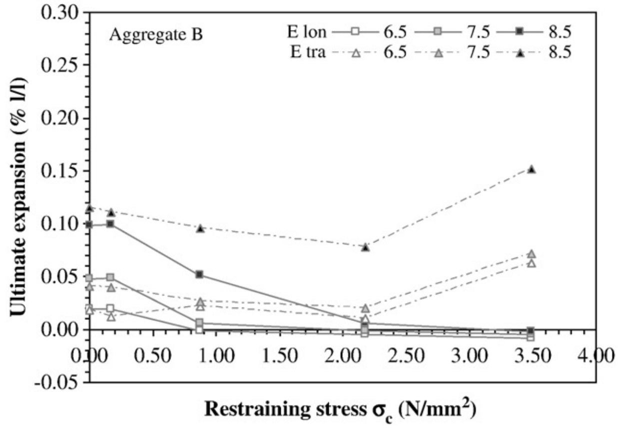

Fig. 5. Unrestrained and restrained (longitudinal and transversal) ultimate expansions vs. restraining stress for concrete mixes made with aggregate B.

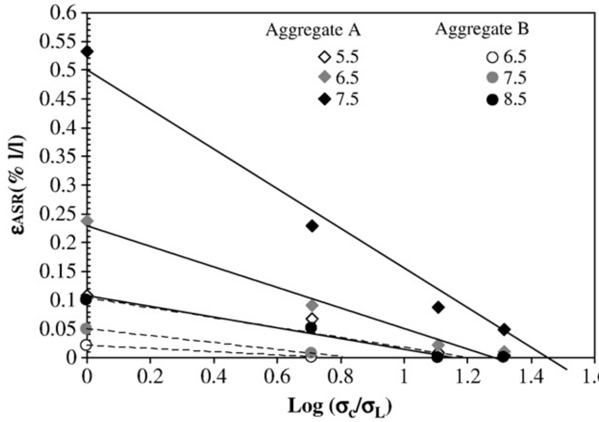

Fig. 7. Correlation of expansion data with the Charlwood's model.

As expected, the ultimate longitudinal expansions gradually vanished as the applied stress was increased. In the case of the concrete mixes made with the less reactive aggregate (B) and subjected to higher stress levels ($\sigma_c = 2.18$ or 3.50 N/mm^2), negative values of E_{lon}% were always recorded up to the ultimate time of testing. These results suggested that, under such test conditions, ASR expansion was suppressed or strongly limited by load application and the observed strain was almost totally attributable to elastic and creep deformations.

The levelling-off of the unrestrained expansions with increasing testing time was not attributable to the exhaustion of reactive material in the aggregates, since the ultimate expansions were found to increase with increasing alkali content of concrete (Fig. 2). Thus, the observed levelling-off of the expansion was ascribed to the equilibration between the alkali concentration and ASR gel. In this regard, a possible leaching of alkalis from concrete specimens stored at 38 °C and 100% RH (not investigated in the present study) would contribute to the exhaustion of the alkalis content in the concrete specimens, thus reducing the expansion level attainable with a specific actual L_{ac} value. As a result, leaching could lead to an overestimate of the TAL values of the aggregates.

In Figs. 4 and 5, the ultimate unrestrained and restrained (corrected for mechanical strains) expansions in both longitudinal and transversal directions are plotted against restraining stress, σ_c.

At a fixed concrete alkali level, longitudinal restrained expansions were always lower than longitudinal unrestrained expansions, and the former also decreased with increasing restraining stress. Transversal expansions, E_{tra}%, were generally greater than the corresponding longitudinal ones, E_{lon}% (particularly at higher stress levels), due to the absence of restraint against expansive pressure. This supported the expected anisotropic behaviour of the expansive phenomenon under restrained conditions. Irrespective of the concrete mix considered, the restrained expansions under a compressive stress of 0.17 N/mm^2 were found to be similar to the corresponding unrestrained expansions.

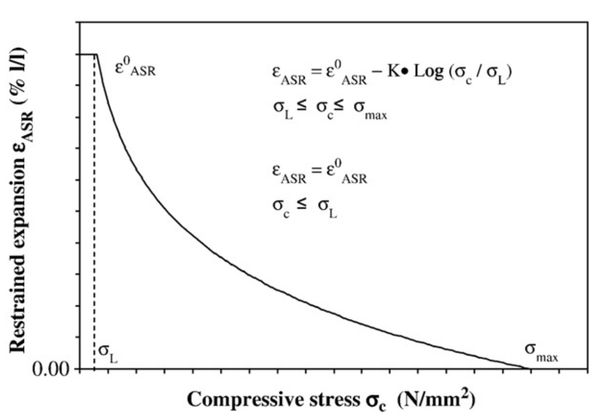

Fig. 6. Relationship between concrete ASR expansion and compressive stress σ_c [9,10].

3.2. Correlation of restrained expansions with a mechanical behaviour model

Using the data of Figs. 4 and 5, relative to the ultimate longitudinal restrained expansions (E_{lon} %), it was possible to verify the validity of the mechanical behaviour model developed by Charlwood et al. [9,10] for predicting the dependence of the ASR gel expansion within a concrete structure on its stress state.

This model assumes the concrete expansion under low compressive stresses as an anisotropic phenomenon and the strain growth rate is resolved to the direction of each principal stress as follows:

$$\varepsilon_{ASR}\% = \varepsilon^0_{ASR}\% - K\cdot \log\left(\frac{\sigma_c}{\sigma_L}\right) \tag{1}$$

where ε_{ASR}% is the restrained ASR expansion at a fixed time t (one year of testing), $\varepsilon^0{}_{ASR}$% is the unrestrained ASR expansion at the same time, σ_c is the compressive stress, σ_L is the stress below which ε_{ASR}% is constant and equal to the unrestrained expansion, and K is the slope of the line defining the strain versus the logarithm of stress.

The stress σ_L is generally taken equal or lower than 0.3 N/mm^2 [9,10].

A graphic representation of the stress-dependent function (Eq. (1)) is provided on Fig. 6, where σ_{max} represents the compressive stress at which no ASR expansion can take place ($\varepsilon_{ASR}\% = 0$).

The ASR expansion, ε_{ASR}%, under a constant applied compressive stress, σ_c, is calculated as:

$$\varepsilon_{ASR}\% = E_{lon}\% + 100\cdot J(t_0, t)\cdot \sigma_c \tag{2}$$

where E_{lon}% is the restrained longitudinal expansion determined experimentally and $J(t_0, t)$ is the viscosity function related to the total (elastic and creep) mechanical strain [8]. Total mechanical deformations up to a maximum of 0.022% and 0.020% were, respectively, calculated for

Table 1
Values of maximum compressive stress, σ_{max}, calculated from Charlwood's model.

L_{ac} (kg Na_2O_{eq}/m^3)	σ_{max} (N/mm^2)	
	Aggregate A	Aggregate B
5.5	2.3	–
6.5	3.2	0.8
7.5	4.9	1.1
8.5	–	2.2

the concretes made with aggregate A ($J(t_0,\ t) = 6.2 \cdot 10^{-5}$) and aggregate B ($J(t_0, t) = 5.8 \cdot 10^{-5}$) at the highest stress level investigated ($\sigma_c = 3.50$ N/mm^2).

The ε_{ASR}% values thus calculated corresponded to the ultimate restrained longitudinal expansions reported in Figs. 4 and 5.

In some cases, the calculated ε_{ASR} values resulted to be slightly negative (not lower than −0.007%) (Fig. 5) and this was due to a little underestimate of $J(t_0,\ t)$. The negative values of ε_{ASR}, as well as the positive ε_{ASR} values of less than 0.005% were taken equal to zero in correlating ε_{ASR} with σ_c.

On the basis of the data in Figs. 4 and 5, the value of $\sigma_c = 0.17$ N/mm^2 was taken equal to σ_L in Eq. (1) and this value was congruent with those reported by Charlwood et al. [9,10].

Fig. 7 shows the correlation of the expansion data with the Charlwood's model (Eq.(1)).

The results in Fig. 7 proved the validity of the mechanical model and allowed the determination of the compressive stress, σ_{max}, at which no ASR expansion will occur within the concrete mix considered (aggregate type and/or alkali content).

The stress σ_{max} was calculated as:

$$\sigma_{max} = \sigma_L \cdot 10^m \tag{3}$$

where m is the value of $\log(\sigma_c/\sigma_L)$ corresponding to the intercept of each straight line with the abscissa axis (Fig. 7).

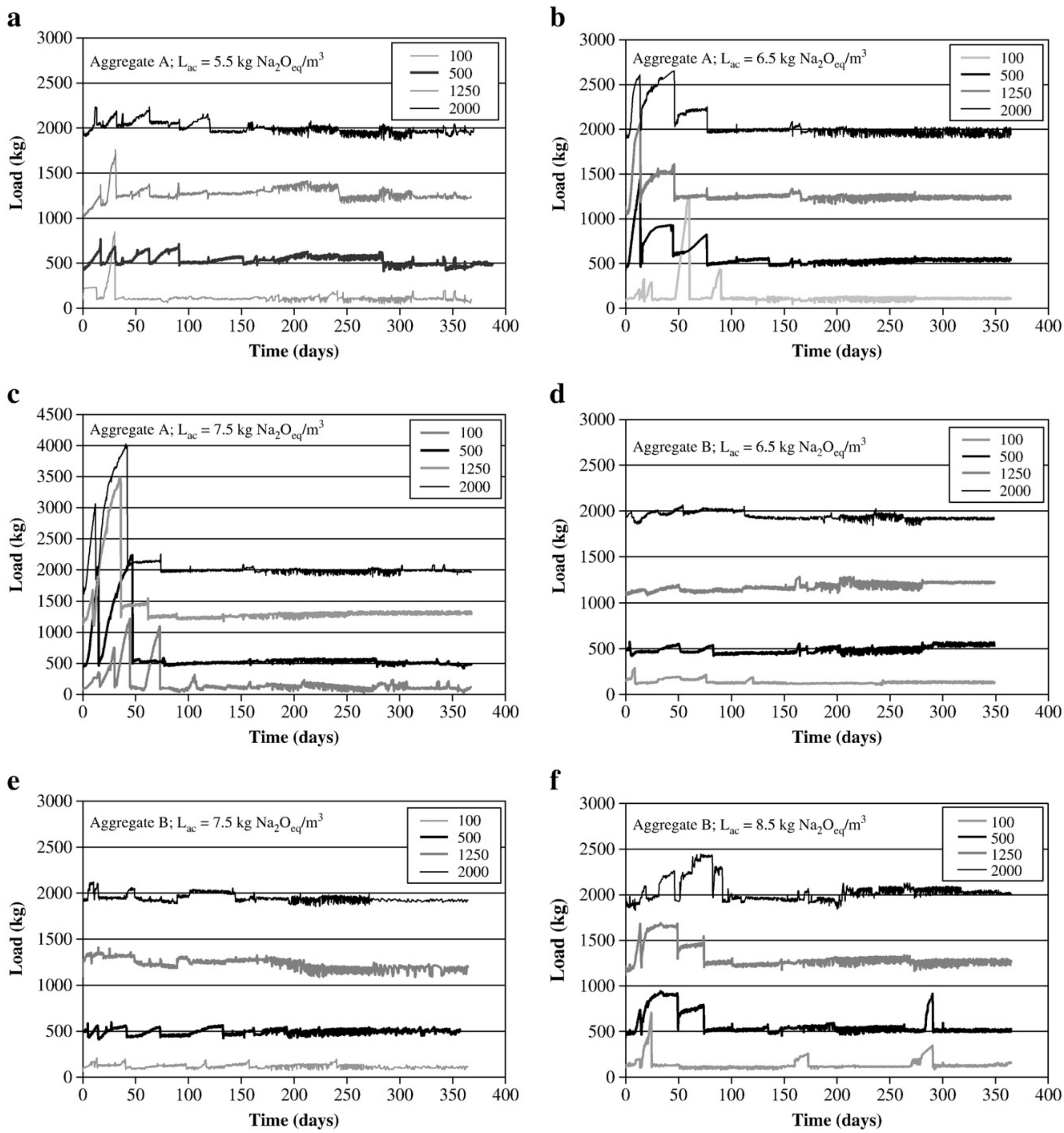

Fig. 8. a–f, — Load patterns for concrete specimens made with aggregates A and B and different alkali contents ($\sigma_c = 0.17$ MPa, load = 100 kg; $\sigma_c = 0.87$ MPa, load = 500 kg; $\sigma_c = 2.18$ MPa, load = 1250 kg and $\sigma_c = 3.50$ MPa, load = 2000 kg).

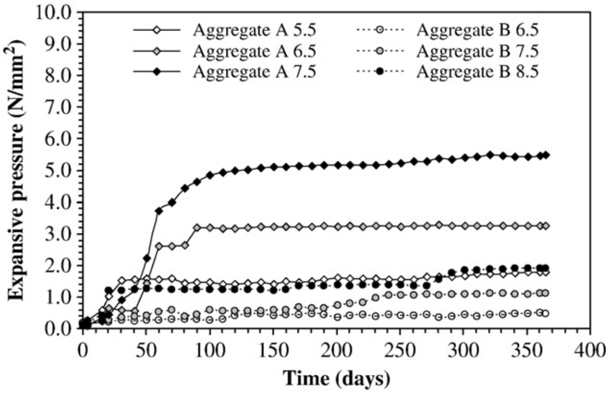

Fig. 9. Development of "free" expansive pressure (under the lowest restraining stress of 0.17 N/mm^2) for all concrete mixes investigated.

Table 1 gives the values of σ_{max} obtained for the various concrete mixes investigated.

As expected, σ_{max} increased significantly with increasing aggregate reactivity and/or concrete alkali content.

3.3. Expansive pressure development

Fig. 8a–f shows the complete load patterns registered during the restrained expansion tests under different initial compressive stresses (0.17–3.5 N/mm^2) for the concrete specimens made with aggregate A at alkali levels, L_{ac}, of 5.5, 6.5 and 7.5 kg Na_2O_{eq}/m^3 (Fig. 8a–c) and for concretes with aggregate B at L_{ac} values of 6.5, 7.5 and 8.5 kg Na_2O_{eq}/m^3 (Fig. 8d–f). Load adjustments were requested to maintain constant load conditions on the concrete specimens. On the basis of these load adjustments, it was possible to determine the expansive pressure, P_g, developed by the ASR gel at different testing times for every concrete mix and restraining stress tested.

In Fig. 9, the expansive pressure, P_g, developed under a minimum restraint of 0.17 N/mm^2 ("free" expansion conditions) is shown plotted as a function of testing time. Table 2 gives the values of the expansive pressure developed after 365 days of testing (ultimate expansive pressure) for all concrete mixes and restraining stresses investigated.

The data in Table 2 and Fig. 9 revealed that, irrespective of the compressive stress applied and the type of aggregate tested, the expansive pressure increased significantly as the concrete alkali content was increased. At the same alkali content, concrete mixes made with more reactive aggregate (A) always developed higher pressures. Furthermore, the development of expansive pressure with time (Fig. 9) was consistent with the corresponding change of expansion with time (Fig. 3), and the ultimate expansive pressure for a specific concrete mix appeared to be virtually unaffected by the compressive stress applied (Table 2). Thus, the average ultimate P_g values for the various types of concrete formulations were calculated (Table 2) and used for subsequent correlations with mechanical or chemical parameters, such as σ_{max} or L_{ac}.

Table 2
Values of ultimate expansive pressure, P_g, at different restraining stresses.

σ_c (N/mm^2)	Aggregate A			Aggregate B		
	L_{ac} (kg Na_2O_{eq}/m^3)			L_{ac} (kg Na_2O_{eq}/m^3)		
	5.5	6.5	7.5	6.5	7.5	8.5
0.17	1.8	3.2	5.5	0.50	1.1	1.9
0.87	1.8	3.1	5.2	0.45	1.3	1.6
2.18	1.9	2.8	5.0	0.57	0.7	1.7
3.50	1.5	3.0	5.6	0.38	1.1	1.8
Average	1.8	3.0	5.3	0.48	1.1	1.8

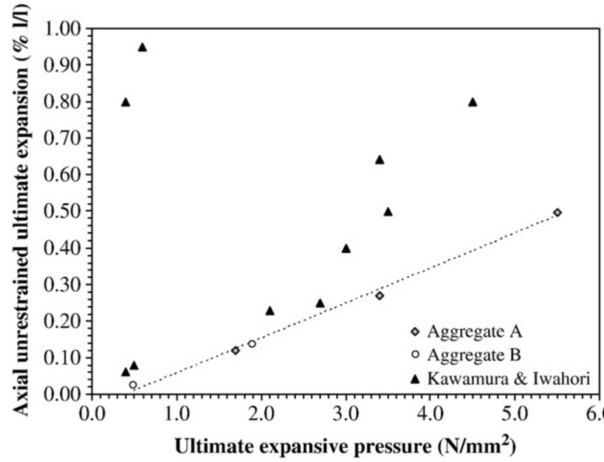

Fig. 10. Axial unrestrained ultimate expansion vs. ultimate expansive pressure (experimental data compared with previously published data from literature [6]).

The results in Table 2 also suggested that, over the range of restraining stresses investigated (up to 3.50 N/mm^2), the development of expansive pressure was not governed by mechanical and physico-chemical phenomena leading to a significant P_g reduction, such as: 1) microcracking of concrete, that increases its porosity [11], and 2) slower ASR development (as compared to unrestrained expansion) with formation of a gel characterised by smaller water absorbing capacity and swelling properties, in analogy to other more known expansive phenomena (e.g., expansive ettringite formation from hydration of calcium sulpho-aluminate $4CaO \cdot Al_2O_3 \cdot SO_3$ in the presence of gypsum and lime) [12].

Fig. 10 shows the relationship between the axial unrestrained ultimate expansions and the corresponding ultimate expansive pressures (Table 2, $\sigma_c = 0.17$ N/mm^2). In this figure, the results of a previous study by Kawamura and Iwahori [6] on mortar specimens are also reported.

The experimental data of the present study showed a linear relationship between expansive pressure and unrestrained expansion and, at least up to an expansive pressure of about 3 N/mm^2, also the data presented in [6] fitted such a relationship (except for the two points at the upper left corner of the plot).

Fig. 11 compares the average P_g values determined experimentally (Table 2) with the corresponding σ_{max} values calculated from Charlwood's model (Table 1).

The reasonable correspondence between these two parameters suggested that σ_{max} may be taken as a measure of the expansive pressure, P_g.

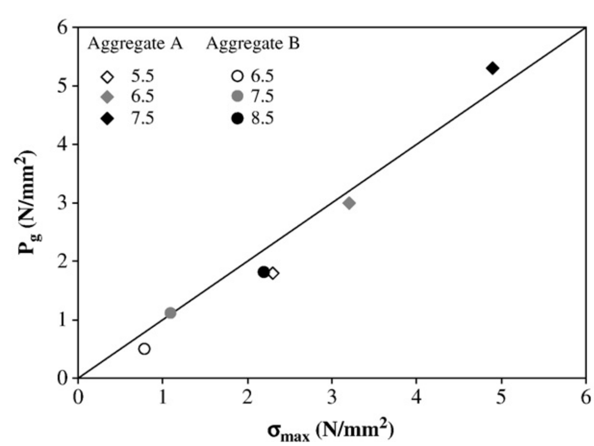

Fig. 11. Comparison between the ultimate expansive pressures determined experimentally and the values of σ_{max} obtained from Charlwood's model.

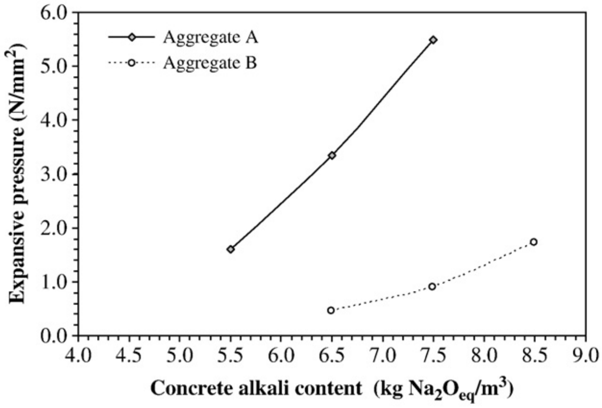

Fig. 12. Ultimate expansive pressure vs. concrete alkali content.

3.4. Relationship between expansive pressure, concrete alkali content, and aggregate TAL

As evidenced by the data in Table 2, even under restrained conditions, the expansive pressure greatly increased with increasing concrete alkali content and/or alkali -reactivity of the aggregate. If the average P_g values of Table 2 were plotted against concrete alkali content, two distinct curves were obtained for the two types of aggregates (Fig. 12).

On the basis of the linear relationship existing between unrestrained expansion and expansive pressure (Fig. 10) and taking in mind the dependence of unrestrained expansion on the driving force for ASR development [3], it was likely to think that the expansive pressure developed by the ASR gel should be in relation with this driving force. The ASR driving force is defined as the difference between the alkali content of concrete, L_{ac}, and the threshold alkali level, TAL, of the aggregate used for the concrete formulation [3].

Fig. 13 shows the average P_g values plotted against the corresponding values of the driving force, L_{ac}-TAL, of the concrete mixes investigated.

As can be noted, irrespective of the aggregate type (TAL) and the concrete alkali content (L_{ac}) considered, a unique exponential relationship between expansive pressure P_g and driving force L_{ac}-TAL can be found. This proved that, even under restrained conditions, the threshold alkali level is a suitable reactivity parameter for designing concrete mixes that will not be susceptible of deleterious ASR expansion during their service life. Such mixes can be formulated by selecting aggregates with TAL values higher than the maximum concrete alkali content expected during the structure service life.

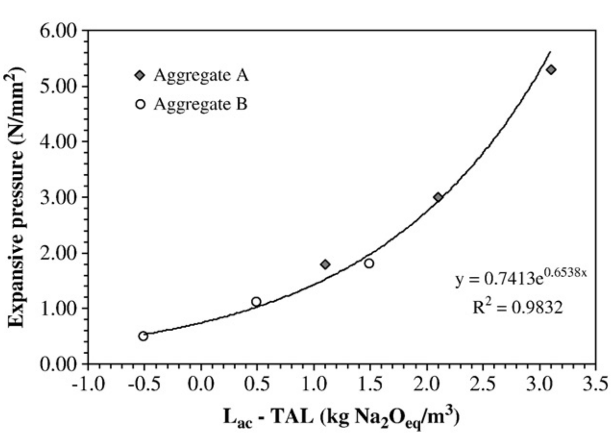

Fig. 13. Ultimate expansive pressure vs. driving force for ASR development.

From Fig. 13 it can also be observed that, when the concrete alkali content is equal to the threshold alkali level of the aggregate, i.e. for an axial unrestrained expansion equal to 0.05% (expansion limit suggested by RILEM [5]), the expansive pressure is about 0.75 N/mm^2.

The relationship of Fig. 13 may be useful to quantify, for a specific concrete composition, the key parameters (σ_{max} and K in the Charlwood's model) required for modelling the restrained ASR development in ASR-affected concrete structures.

4. Conclusions

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

The ASR expansion under restraining stress may be successfully predicted from the Charlwood's model.

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 threshold alkali level, 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.

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

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