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Internal expansive reactions in concrete structures – deterioration of the mechanical properties

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Abstract

A significant number of problems related to concrete deterioration were detected in Portugal and worldwide due to the development of internal expansive reactions (IER). Their negative effect has important economic implications because they are the main cause of degradation of large concrete structures. In addition, the work necessary to remediate the problem involves large areas of reconstruction and complex and expensive rehabilitation techniques and materials. Moreover, IER diminishes the affected structure service life, may involve the interruption of its function and, ultimately, can lead to its decommissioning and demolishing. Therefore, a study is being conducted at LNEC to diminish their negative impact by increasing knowledge on how to reliably assess their extent and potential for future development in existing structures. To study the effect that IER have in the deterioration of concrete, the common practice is to perform tests on specimens exposed to an artificial environment that promotes IER. However, these tests take several months or years to produce results. Thus, this paper presents the preliminary work carried out to devise a method capable of producing internal damage to concrete in a short period and in a way that the produced deterioration affects the concrete mechanical properties similarly to IER.

Keywords: concrete; deterioration; internal expansive reactions; mechanical properties; internal damage; test method.

1. Introduction

In the last decade, a significant number of problems related to concrete deterioration have been detected in large concrete structures (*e.g.* dams and bridges) in Portugal and throughout the world; the leading cause being internal expansive reactions (IER), more specifically, alkali-silica reaction (ASR) and internal sulphatic reaction (ISR).

ASR is a chemical reaction between the alkali hydroxides in the concrete pore solution and some siliceous minerals present within certain aggregates. The reaction results in the formation of a calcium-rich alkali-silica gel that is hydrophilic and expands in the presence of water causing the disruption of concrete [1,2].

ISR is a chemical reaction between sulphate ions and calcium aluminates present in the hardened cement paste that results in the formation of ettringite. As the name suggests, the source of sulphate is in the concrete and can be the cement, the supplementary materials (*e.g.* fly ash), the aggregate, or the chemical admixtures. The formation of the so-called secondary or delayed ettringite has an expansive nature and can cause the disruption of concrete [2-4].

If sufficient IER occurs in the concrete, the induced pressures cause micro-cracking and then expansion of the surrounding concrete. The concrete surface does not expand to the same extent as the interior, because the conditions required for the reactions are not totally fulfilled at the concrete surface, for example, the concrete surface is subject to leaching of the alkalis

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and to temperatures lower than those felt in the bulk of the concrete mass. This causes tensile stresses to arise in the surface and induce surface macro-cracks. The formation and orientation of both micro- and macro-cracks are affected by restraint that also reduces expansion. Generally, IER generate a very significant drop in terms of tensile strength and modulus of elasticity, whilst the compressive strength only begins to decrease significantly at high levels of expansion [4,5].

Hence, the structural integrity of large concrete structures can be severely jeopardized by both ASR and ISR evolution, which ultimately can lead to their decommissioning and demolishing. Currently, there is no effective way of stopping ASR and ISR, however, in some cases they can be slowed down through rehabilitation works.

The first reports on ASR were published in 1940 [6,7]. In the following decades the essential requirements for its occurrence were identified (sufficient moisture in concrete and appropriate relative proportions of alkali hydroxides in pore solution and reactive siliceous material in aggregate), and the first regulations to prevent ASR were created. However, the structures built according to them also developed ASR [1].

The ISR is relatively newer with respect to ASR, since it was only detected in the middle of 1980s in pre-stressed concrete railway ties [8]. The essential requirements for its occurrence consist of high temperature during concrete cure (> 65 ºC), a sufficient amount of alkali, SO_3 and C_3A in the cement, a sufficient moisture content in concrete, and an appropriate amount of calcium hydroxide in the concrete pore solution [4]. The deleterious effects of ISR may be enhanced by the initial development of cracks due to ASR or other factors, through the crystallization of ettringite in these cracks that will lead to additional expansion of the concrete.

Since then a vast amount of research has been conducted and the understanding on IER has progressed significantly. However, the problem was not totally eradicated as today numerous concrete structures still exhibit ASR and ISR. The reasoning behind the detection of an increasing number of affected structures is threefold, greater awareness of the technical and scientific community regarding IER, improvement of the methods utilized in IER diagnosis, and the fact that distress signs can appear only several years or decades after construction.

Current knowledge on IER does not allow for a complete assessment of the actual condition of an IER affected structure and an accurate prediction of the mechanical properties deterioration and, consequently, of the period during which the structure will effectively perform its function, essential for the timely and cost-effective planning of the necessary mitigation/rehabilitation/reconstruction works. This is of upmost importance in large concrete structures, where IER can have severe consequences in terms of structural safety and serviceability [9,10]. The importance of this type of structures, the number of structures in which IER was already identified or is very likely to be diagnosed in a near future, the large number of structures that are under or planned for construction, which may also come to develop IER is why, today, they are still a major concern.

Therefore, to help surpassing this situation, a research project is being conducted at LNEC to contribute to the establishment of a method for the accurate determination of the current level of IER progression and of the deterioration of the concrete mechanical properties. These are essential to the adequate overall appraisal of an affected structure, and the development of structural models that predict risks to structural integrity, potential for further deterioration due to other mechanisms, need for mitigation/remediation actions, and the remaining service life of the affected structure, as acknowledged in the "IStructE ASR Technical Guide" [11] and "IStructE Appraisal of existing structures" [12]. This paper presents the preliminary results, from the aforementioned study, concerning the assessment of the effect that internal expansion has in the deterioration of the concrete mechanical properties, more specifically in its stiffness, currently considered has being the concrete mechanical property most sensitive to deleterious expansion [5,11].

2. Experimental programme

Concrete deterioration due to IER is a very slow process and it is normally studied through the conduction of expansion tests carried out on mortar or concrete prisms exposed to an artificial environment that accelerates the reactions. For promoting ISR, the current practice is to immerse concrete specimens in water at ambient temperature. In order to promote the development of ASR, it is current practice to expose concrete specimens to high relative humidity (> 95 %) and a temperature of 38 ºC or 60 ºC. However, even with these accelerated tests, the results are obtained only after several months or years of testing. Therefore, an experimental campaign was devised to seek methods of producing internal damage to concrete in a short period, but that do so in a way that the produced deterioration affects the concrete mechanical properties similarly to IER.

The test campaign was carried out on concrete prisms (285x75x75 mm) equipped with stainless steel reference studs bonded into the mid-points of the end faces of the prisms for measuring length changes, and comprised two different approaches to impart internal damage to concrete. The first approach (A) consisted of exposing the prisms to thermal shocks after a determined concrete curing period. The second approach (B) consisted of using an expansive binder and then to subject the concrete to two different curing procedures. Table 1 summarizes the test campaign.

Table 1. Test campaign.

Groups	Internal damage inducing actions	Tests
1	None	Length change, Ultra-sounds, Stiffness test
2a, 2b	2 h in water at 70 ºC + 2 h in water at 0 ºC (38 repetitions)	
3a, 3c	24 h in air at +26 ºC → -22 ºC → +26 ºC + 24 h in water at 20 ºC (11 repetitions)	
3b, 3d	24 h in air at 100 ºC + 24 h in water at 20 ºC (11 repetitions)	
4a, 4b	Expansive agent (28 d wet cure at 20 ºC followed by a 48 h post cure at 40 ºC)	
4c, 4d	Expansive agent (28 d cure at 20 ºC followed by a 48 h wet post cure at 40 ºC)	

Note: Each one of the 11 groups was composed of three replicates.

The concrete compositions and the mixing procedure used are presented in Tables 2 and 3, respectively.

Table 2. Concrete compositions (kg/m^3).

	Groups 1, 2a, 2b	Groups 3a, 3c, 4a, 4c	Groups 3b, 3d, 4b, 4d
Cement (CEM I 42.5R)	440	380	350
Expansive agent	0	60	90
Water	220	220	220
Superplasticizer	2.2	2.2	2.2
Fine aggregate (0-4.0 mm)	650	642	637
Coarse aggregate (4.0-22.4 mm)	985	972	965

Note: Groups 3 and 4 used the same expansive agent. Two groups were made, because during the concrete curing of group 3 specimens no expansion was observed, meaning that the expansive agent did not work properly (since the expansive agent batch was already two years old when it was used, it most likely reacted with the ambient moisture during storage and thus did not hydrate in the extent expected during the test campaign); therefore, a new batch of the expansive agent was used thus creating the group 4 specimens. Because of this, and in order not to discard the specimens, it was decided to expose group 3 specimens to internal damage inducing environments. Each mould allowed to fabricate three specimens; thus, to identify the specimens that came from separate moulds, a letter was added next to the group number.

Table 3. Concrete mixing procedure.

Time	Action	Total elapsed time
0 s	Addition of aggregates	60 s
60 s	Addition of ½ of the total water	120 s
120 s	Pause	180 s
180 s	Addition of binder and second ½ of the total water with the superplasticizer	300 s

All concrete compositions used limestone aggregates. The granulometric curve for the aggregates lies within the limits specified in [13] (Figure 1).

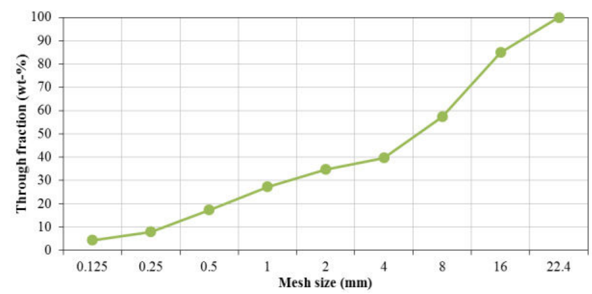

Fig. 1. Particle size distribution of the aggregates used in the tests.

The preparation and filling of the moulds was performed according to EN 12390-2 [14]. All test specimens were left in the moulds for 24 hours, protected against shock, vibration and dehydration (with a polyethylene sheet) in a room at a temperature of (20 ± 2) ºC and high relative humidity (≥ 95 %). After removal from the moulds, the test specimens were cured in water at a temperature of (20 ± 2) ºC for 28 days and then wrapped in polyethylene sheet and placed in a chamber at (40 ± 2) ºC for 48 h. The specimens of groups 3c, 3d, 4c and 4d were subjected to a different cure procedure; namely, after removal from the mould, the test specimens were wrapped in polyethylene sheet and cured in room at a temperature of (20 ± 2) ºC and relative humidity ≥ 65 % for 28 days.

The specimens' mass and length change was registered throughout the test campaign. The length change measurements were performed according to RILEM Test Method AAR-4.1 [13]. The ultrasonic pulse velocity (UPV) measurements were performed using a PUNDIT Ultrasonic Test equipment (CNS Electronics Ltd., London, England) with transit time resolution of 0.1 µs and generally following the EN 12504-4 [15]. The UPV measurements were made by placing the two transducers on the end faces of the concrete prisms (direct transmission). The stiffness test used derives from that defined in [16-18] and consists of submitting the specimens to five cycles of uniaxial loading/unloading between 1 and 10 MPa while recording the stress and strain.

3. Results and discussion

3.1. Length change measurements

In terms of the approaches used to impart internal damage to concrete, it is readily seen that expansions were only detected for the specimens exposed to thermal shock (by passing from water at 70 ºC to water roughly at 0 ºC) and for those which incorporated an expansive agent in their composition (Table 4).

Table 4. Results from the length change measurements.

Groups	Internal damage inducing actions	Expansion (%)
1	None	0.004
2a, 2b	2 h water 70 ºC + 2 h water 0 ºC	0.011
3a, 3c	24 h air (26 ºC → -22 ºC → 26 ºC) + 24 h water 20 ºC	0.003
3b, 3d	24 h air 100 ºC + 24 h water 20 ºC	0.001
4a	Expansive agent (28 d wet cure at 20 ºC	0.009
4b	followed by a 48 h post cure at 40 ºC)	0.017
4c	Expansive agent (28 d cure at 20 ºC	0.005
4d	followed by a 48 h wet post cure 40 ºC)	0.009

The specimens exposed to freeze-thaw cycles apparently did not produce any expansion. The freeze-thaw environment is known to impart internal damage to concrete accompanied by expansion [19-21], therefore the results obtained most likely derive from the low number of cycles undertaken up to the moment of testing. Because of that, after the length change and UPV measurements and the stiffness tests, new stainless steel reference studs were bonded into the mid-points of the end faces of the prisms and the specimens returned to the freeze-thaw cabinet to prolong the test.

In what concerns the concrete exposed to harsh drying and wetting cycles, it would also be expected that those conditions result in some internal damage to the concrete, possibly with an expansion associated with it; however, no expansion was detected for the specimens subject to these cycles (Table 4). When concrete is exposed to repeated drying and wetting, the drying shrinkage exhibits a certain degree of irreversibility. Normally, after the first drying, concrete does not return to the original dimensions on rewetting. This is why drying shrinkage is usually categorized into reversible shrinkage (which is the part of total shrinkage that is reproducible on wet-dry cycles) and irreversible shrinkage (which is the part of total shrinkage on first drying that cannot be reproduced on subsequent wet-dry cycles) [22]. It is though that the irreversible drying shrinkage is probably due to development of chemical bonds within the C-S-H structure as a consequence of drying [22]. In the present case, the results suggest that an irreversible drying shrinkage might have occurred and, possibly, this has masked or restrained the expansion associated with the internal damage.

3.2. Ultrasonic pulse velocity measurements

The ultrasonic pulse velocity measurements were made with the aim of obtaining an indication of the damage level imparted to the concrete specimens using the different approaches. The main variations consisted of a clear increase in the UPV for the reference specimens and a clear decrease for the specimens of groups 3b, 3d, 4c and 4d (Table 5).

Table 5. Results from the ultrasonic pulse velocity measurements.

Groups	Internal damage inducing actions	$UPV_{initial}$ (m/s)	UPV_{final} (m/s)	$\Delta UPV_{final\text{-}initial}$ (m/s)
1	None	4856	4980	124
2a, 2b	2 h water 70 ºC + 2 h water 0 ºC	4854	4857	3
3a, 3c	24 h air (26 ºC → -22 ºC → 26 ºC) + 24 h water 20 ºC	4778	4824	47
3b, 3d	24 h air 100 ºC + 24 h water 20 ºC	4712	4265	-447
4a	Expansive agent (28 d wet cure followed by a	n/d	4780	7*
4b	48 h post cure at 40 ºC)	n/d	4759	-14*
4c	Expansive agent (28 d cure followed by a 48 h	n/d	4697	-76*
4d	wet post cure at 40 ºC)	n/d	4640	-133*

Note: The initial UPV was not determined for group 4 specimens (n/d), because the expansion due to the expansive agent happens mostly in the first days of cure (the actual expansion rate will vary according to the curing procedures applied) and their composition is identical to the respective specimens in group 3. Therefore, the initial UPV for group 4 specimens was considered to be similar to that of group 3 specimens so that the $\Delta UPV_{final\text{-}initial}$ values presented and marked with an * were calculated using the $UPV_{initial}$ of group 3 specimens.

In terms of the initial UPV measurements, very small differences were observed for the different compositions. In spite of the attempt of using similar compositions in the test campaign, the total amount of aggregate varied slightly between compositions that incorporate and do not incorporate an expansive agent, and between those that incorporate an expansive agent at different dosages. Therefore, the higher UPVs were attained for compositions 1, 2a and 2b (1635 kg of aggregates), followed by compositions 3a and 3c (1614 kg of aggregates) and then by compositions 3b and 3d (1602 kg of aggregates); which appear to indicate that these differences might be related to the aggregate content [23]. The increase in UPV observed for the reference specimens is most likely related to the evolution of cement hydration [24]. The decrease in UPV obtained for specimens 3b and 3d and the low values obtained for group 4 specimens suggest the existence of micro-cracking in the concrete, because discontinuities in the concrete increase the travel time of the ultrasonic wave pulse between the two transducers [22].

3.3. Stiffness determination

The stiffness test was used to assess the internal damage in concrete resulting from expansion, because it allows determining two parameters that are believed to be a good indicator of the internal micro-cracking level; namely the elastic modulus and the energy dissipated during the first load-unload cycle. Generally, the modulus of elasticity decreases with the increasing internal micro-cracking in concrete [5, 11, 22] and the dissipated energy increases with the progress of internal micro-cracking and expansion in concrete [17].

The main differences observed for these two parameters in relation to those obtained for the reference concrete (Table 6), consisted of a clear decrease in the $E_{c,S1C}$ and a clear increase in the $DE_{c,1C}$ for the specimens from groups 3b, 3d, 4a, 4b, 4c and 4d. In addition, both parameters allowed to observe a variability in the deterioration level amongst these groups, showing that the most damaged specimens were those of groups 3b, 3d, 4c and 4d; and the least damaged were those from groups 2a, 2b, 3a and 3c.

Table 6. Results from the stiffness tests.

Groups	Internal damage inducing actions	$E_{c,S1C}$ (GPa)	$DE_{c,1C}$ (J/m^3)
1	None	36	82
2a, 2b	2 h water 70 ºC + 2 h water 0 ºC	35	87
3a, 3c	24 h air (26 ºC → -22 ºC → 26 ºC) + 24 h water 20 ºC	34	90
3b, 3d	24 h air 100 ºC + 24 h water 20 ºC	24	294
4a	Expansive agent (28 d wet cure	33	118
4b	followed by a 48 h post cure at 40 ºC)	31	157
4c	Expansive agent (28 d cure followed	32	118
4d	by a 48 h wet post cure at 40 ºC)	30	186

Note: $E_{c,S1C}$ = Modulus of elasticity, considered to represent the stiffness of the specimen (obtained from the slope of the first loading curve); $DE_{c,1C}$ = Energy dissipated during the first load/unload cycle.

These results are in agreement with the UPV measurements (Table 5). The results from the length change measurements are, in general, in accordance with the ones obtained in the stiffness tests (Tables 4 and 6); however, the latter allowed clarifying the actual level of damage. For instance, it is possible to observe that, in spite of the absence of expansion registered for specimens from groups 3b and 3d, they actually exhibited the highest level of internal damage in the stiffness test. This is indicative that the harsh environment did induce damage to the specimens; however, it was masked by the irreversible drying shrinkage. Apparently, the stiffness test did not detect any significant internal damage for specimens 2a and 2b, even though they exhibited an expansion. For group 4 specimens, the observed expansions were in agreement with the results from the stiffness test, *i.e.*, the specimens with the higher expansions also presented the larger decrease in $E_{c,S1C}$ and increase in the $DE_{c,1C}$, and vice versa. For comparison purposes, the typical relation between the elasticity modulus and the dissipated energy in two IER affected concrete structures depicted in Figure 2, being clearly visible the relation between the two parameters.

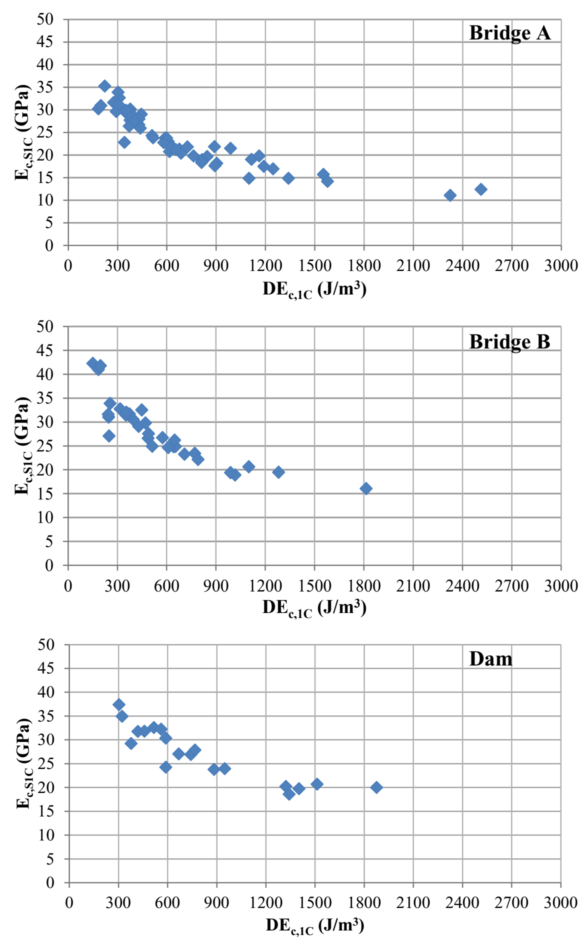

Fig. 2. Representation of the elasticity modulus (obtained from the slope of the first load/unload cycle) *versus* the energy dissipated during the first load/unload cycle obtained for cores extracted from two concrete bridges and one concrete dam.

As it was already said, the main objective of this preliminary work was to seek methods of producing internal damage to concrete in a short period, but that do so in a way that the produced deterioration affects the concrete mechanical properties similarly to IER. From the several methods tested, the most promising was the one involving an expansive agent in the concrete composition and with the 28 d wet cure at 20 ºC followed by a 48 h post cure at 40 ºC. This is due to the fact that the specimens containing an expansive agent and cured with that method exhibited a relevant expansion in a short period of time, accompanied by internal damage, and also because, for those specimens, the plot representing $E_{c,S1C}$ versus expansion (Figure 3) exhibited a behaviour closest to that observed by IStructE [11] for the variation of the elasticity modulus with the expansion due to ASR. Nevertheless, this will be better confirmed when the test campaign is complete and data from specimens presenting a larger expansion and damage are obtained and analysed.

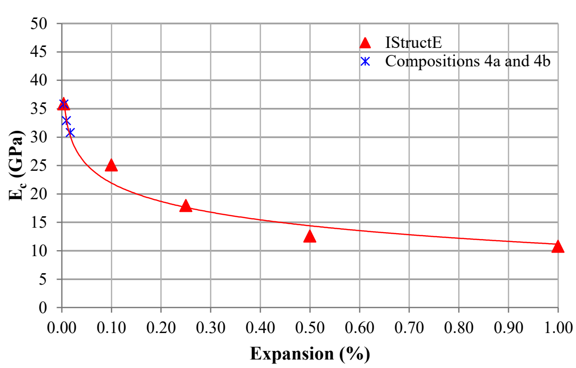

Fig. 3. Representation of the elasticity modulus (obtained from the slope of the first load/unload cycle) versus the expansion obtained for the reference concrete and for concrete compositions 4a and 4b. Overlaid in the same graphic is the variation of the elasticity modulus with the expansion due to ASR according to IStructE [11] for expansion values higher than 0.10 %.

4. Conclusions

This paper presents the preliminary work developed within the ongoing research project at LNEC, which aims to contribute to the establishment of a method for the accurate determination of the current level of IER progression and of concrete mechanical properties deterioration due to IER. Thus, the work here presented intended to show if any of the evaluated methods would be capable of producing internal damage to concrete in a short period while producing deterioration that affects the concrete mechanical properties in a way similar to that caused by IER. The main conclusions from this work can be summarized as follows:

- Expansions were only detected for the specimens exposed to thermal shock (by passing from water at 70 ºC to water roughly at 0 ºC) and for those which incorporated an expansive agent in their composition.
- UPV values clearly lower than those obtained for the reference concrete, were observed for specimens of groups
  - 3b and 3d (24 h in air at 100 ºC + 24 h in water at 20 ºC; 11 repetitions).
  - 4a and 4b (expansive agent; 28 d wet cure followed by a 48 h post cure at 40 ºC).
  - 4c and 4d (expansive agent; 28 d cure followed by a 48 h wet post cure at 40 ºC).
- From the stiffness tests, it was possible to observe that,
  - in spite of the absence of expansion registered for specimens from groups 3b and 3d, they actually exhibited the highest level of internal damage in the stiffness test.
  - the stiffness test did not detect any significant internal damage for specimens 2a and 2b, even though they exhibited an expansion.
  - for group 4 specimens, the observed expansions were in agreement with the results from the stiffness test, *i.e.*, the specimens with the higher expansions also presented the larger decrease in the elasticity modulus and increase in the dissipated energy and vice versa.
  - the most promising method to produce internal damage to concrete, in a short period and in a way that the produced deterioration affects the concrete mechanical properties similarly to IER, was the one involving an expansive agent in the concrete composition and with the 28 days wet cure at 20 ºC followed by a 48 hours post cure at 40 ºC.

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