ALKALI-AGGREGATE REACTION: FROM PROGNOSIS TO INTERVENTION

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Abstract

The problem of managing concrete structures affected by alkali-aggregate reaction (AAR) is quite complex, particularly in relation to the prognosis of damaged structures. Till now, a reliable method to determine the potential for further deterioration was not available. In this work, an approach is suggested for the management of AAR damaged structures. Fifteen concrete structures showing typical signs of AAR were studied. Cores were taken from the structures and subjected to microscopy observations, physical and mechanical investigations to identify the cause of concrete deterioration. Once AAR pathology was diagnosed, part of these cores were used for laboratory tests for prognosis purposes. The cores were immerged in 1N sodium hydroxide solution at 40°C and changes in dynamic elastic modulus were monitored for up to six months to determine the potential for further reaction. Data related to dynamic modulus fluctuations in time were suitably interpreted for each element of the monitored structures.

Keywords: alkali-aggregate reactivity; damage management; AAR diagnosis; remedial intervention.

1 INTRODUCTION

Alkali-aggregate reaction in concrete consists of the dissolution of amorphous or certain crystalline silica phases contained in the aggregates by hydroxyl ions. The ions are produced within the cement paste by the hydration reaction of high-alkali cements. The reaction product is a silica gel that can absorb great quantities of water and expand, causing tensile stresses in the surrounding paste or aggregate and often generate enough internal pressure to crack the concrete. The cracking severity seems to be dependent on the rate of internal expansion, on the surrounding environment and on the degree of restraint present in a given concrete volume. The presence of water is essential for the reaction to develop; in fact, it is generally agreed that alkali-aggregate reactivity can develop or sustain in concrete if its internal relative humidity is higher than 80-85%, Stark [1].

Nowadays, the alkali-aggregate reaction (AAR) is increasingly responsible for significant concrete damage in a great number of reinforced concrete structures throughout the world, and a method for predicting the residual mechanical performance of affected structures is urgently required. The management of structures affected by alkali-aggregate reaction is a complex problem and it includes the diagnosis of AAR, the evaluation of its potential for future deterioration, the mitigation of its deleterious effects and the repair intervention, Fournier et al. [2]. For proper management, time availability for either the intervention of restoration or the partial substitution in safety conditions should be considered.

Determining whether or not the potential still exists for expansive alkali-silica reaction in concrete is quite difficult. Several methods have been proposed to evaluate this, but their validity is limited to either aggregate or cement-aggregate combination [3]: petrographic examination of aggregate (ASTM C 295 [4] and RILEM AAR-1[5]), accelerated mortar-bar test (ASTM C 1260 [6]), quick chemical method (ASTM C 289 [7]), concrete prism test (ASTM C 1293 [8]). Nevertheless, in most practical cases it is also necessary to evaluate the alkali-silica reactivity potential of the hardened concrete of the affected structure in service. This work refers to fifteen concrete structures, which show clear signs of AAR; they were built with concretes whose composition could not be known in detail, so they could not be reproduced in laboratory. Therefore, a test based on cores extracted from these damaged structures was necessary. A few experimental procedures meeting this requirement can be found in the literature, which were set up by Stark [9], Saint-Pierre et al. [10] and Collepardi et al. [11].

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In particular, this work is based on the latter procedure and suggests some improvements in addition to a different way of interpreting experimental data.

2 METHODS FOR DIAGNOSIS AND RESULTS

The first step was a visual survey complemented by coring of some structural elements belonging to fifteen bridge structures, which showed typical signs of alkali-aggregate reaction (AAR), see Figure 1. Laboratory tests were performed on these cores by means of both microscopy examination and physical investigation to assess the cause of concrete deterioration, in particular to identify the cause of cracking.

Core samples were examined, with reference to ASTM C 856 [12], by using both optical microscope (Wild M 420) and scanning electron microscope (Philips XL-20) in order to identify the presence of typical products originated by AAR, see Figure 2 and 3 respectively. The alkali-silica reaction (ASR) typically produces an alkali-silica gel containing silicon as major component with lower contents of sodium, potassium and calcium [2]. Figure 2 shows significant micro-cracking and abundant deposits of reaction products, mainly at the interface between aggregate and cement paste. Figure 3 shows a section of concrete relative to a plane of detachment due to micro-cracking observed by means of the optical microscope at a larger magnification than the image in Figure 2. As can be observed, the gel is once again present, filling the pores and lining the cracks between the aggregate particles and the cement paste.

The results obtained by relative energy dispersive x-ray analysis (EDXA Phoenix) on specimens observed under the scanning electron microscope (Figure 4) confirmed the presence of these secondary reaction products. In particular, in the examined amorphous product, alkalis (such as K) besides silicon were detected, thus confirming the glassy material to be, mainly based on hydrated alkaline silicate of the alkali-silica gel originated by ASR.

3 METHODS FOR PROGNOSIS AND RESULTS

3.1 Mechanical characterization and results

The coring locations in the structures were carefully considered on the basis of structural analyses so that the structure safety was not compromised and the most representative parts of the structures could be chosen. Data concerning the compressive strength of the concrete cores extracted from the two bridge structures are reported in Table 1, according to UNI EN 12390-3:2003.

If the design strength of the structural concrete were to be known, the mechanical properties of the concrete cores would be extremely significant in terms of estimate of the concrete deterioration. In actual fact, this information is hardly ever available, making this approach impossible. Nevertheless, the knowledge on the present state of the concrete (by means of the concrete core testing) together with its potential for further AAR could be enough to predict the future development of concrete deterioration. For this purpose, an accelerated laboratory test developed by Collepardi et al. [11] that can provide a reasonable prediction of the amount of expansion remaining within the concrete, could become useful.

3.2 Accelerated laboratory test and results

The prognosis of concrete structures affected by AAR is aimed at establishing their potential for future deterioration [2]. In particular, it would be helpful to know how much time the structure can safely be in service before either rehabilitation or partial substitution of the most deteriorated structural elements has to be carried out. Moreover, if the phenomenon involves different parts of the same structure or several structures, as in this case, an attempt could be made in order to establish, relatively, the different extent of damage and, consequently, the priority of intervention.

For this purpose, accelerated laboratory tests were carried out. Their experimental methodology consists in submerging the cores taken from damaged structures in 1N sodium hydroxide solution (NaOH) at 40°C to accelerate the AAR, see Collepardi et al [11]. In the meantime, changes in dynamic elastic modulus of the submerged concrete cores are monitored (in this case for 200 days of exposure), in order to try to evaluate the potential for further reaction, which mainly depends on the amount of residual reactive material.

This test was carried out for the cores extracted from several bridge structures. Table 1 shows some physical and mechanical properties of concrete cores taken from different parts of two damaged bridges (eg. Table 1, 'Structure 1' and 'Structure 2'). The poor quality of the concrete that constitutes the bridge piers is quite evident, the reason being a severe damage due to AAR, which the unchanged specific gravity combined with the severe compressive strength loss suggests. The same level of deterioration was not detected for the concrete girders, bearing blocks and abutments. An explanation may lie in the absence of water splashing on these structural elements and consequently in a largely reduced reaction development, as opposed to a possible explanation based upon a different composition or aggregate type used to manufacture the original concrete, hitherto unknown anyway.

The dynamic modulus of elasticity was determined by ultrasonic pulse velocity measurements (carried out through Pundit 6 by CNS Farnell). Precisely, the velocity of an ultrasonic pulse in a material, V in m/s, is related to its dynamic elastic modulus, E_d in MPa, as shown in Eq. (1), where ρ corresponds to the material specific gravity and k is a constant value depending on Poisson's ratio ν.

$$V = k \cdot \sqrt{\frac{E_d}{\rho}} \qquad \text{with} \qquad k = \sqrt{\frac{1-\nu}{(1+\nu)(1-2\nu)}} \tag{1}$$

where Poisson's ratio was assumed equal to 0.1.

Figure 5 and 6 show the variation in the dynamic elastic modulus of the concrete cores extracted from the two bridge structures as a function of the time of exposure to the aggressive conditions of the accelerated laboratory test.

4 DISCUSSION

4.1 Discussion of results for the first structure

With regard to the amplitude of the dynamic modulus fluctuations reported in Figure 5, in the cores taken from the piers and abutments (cores 1, 2, 5 and 6) it can be noted that this amplitude progressively attenuates with increasing storage time. This attenuation could be symptomatic of decrease in the potential for further AAR and the initial amplitude of fluctuation may well be related to the amount of reaction product previously formed within the concrete element, from which the core was extracted.

On the other hand, in the case of the cores taken from the bearing block (cores 3 and 4), a progressive increase in the amplitude of fluctuation was detected. In fact, the bearing blocks were more protected than the piers from both the falling rainwater and the rising groundwater. As a consequence, AAR is observed to be slower to develop (see also the mechanical properties reported in Table 1, where the compressive strength of the concrete from the pier is clearly less than that of the concrete from the respective bearing block, most likely due to a different degree of micro-cracking). This fact is consistent with the fluctuation of the dynamic modulus reported in Figure 5 for these cores: the swelling of previous reaction products is rather limited (see the initial part of the curves), while the development of new reaction gel is rather remarkable (see the amplification of the curves with increasing storage time).

4.2 Discussion of results for the second structure

Figure 6 represents the relative changes of the dynamic elastic modulus value vs. storing time in NaOH solution for the second bridge structure. It is important and interesting to consider the amplitude of the fluctuations shown: in some cases (core 'A' and core 'B') it was more and more deadened with elapsed storing time. Also in this case, this attenuation could be a sign of decreasing potential for further AAR development while the initial amplitude of the fluctuation may be related to the amount of reaction products previously formed within the concrete element from which the core was extracted.

Contrastingly, for the cores taken from girders (core 'D' and core 'E'), a progressive increase of the fluctuation amplitude was detected. In this case too, the girders of bridges are more protected than piers from falling rainwater, rising groundwater and water splashing. Therefore, AAR generally would develop more slowly (see the mechanical properties reported in Table 1). This fact is consistent with the fluctuation of the dynamic modulus reported in Figure 6 for these cores: the swelling of previous reaction products is rather limited (see the initial part of the curves), while the development of new reaction gel is again remarkable (see the amplification of the curves with increasing storing time).

In the authors' experience, a careful observation of the diagrams, such as Figures 5 and 6, could become useful to estimate the development of further concrete deterioration. Even if quantitative evaluation of future damage cannot be extrapolated from this kind of data analysis, a relative comparison in terms of expected risk between elements of the same structure and between different AAR affected structures can be carried out. From working on these data, a risk level, which is mainly dependent on the largest fluctuation amplitude, was defined for each monitored structural element. For example, for the structural element labelled as 'core 1' in Figure 5 and core 'A' in Figure 6, the risk level resulted to be the highest. However, it is important to note that every ranking extrapolated from these data is only based on the behavior of the concrete cores and has to be adjusted on the basis of structural aspects, which are equally determinant.

A study on the residual mechanical properties of concrete beams affected by AAR is reported in [13]. Concerning moduli of elasticity, Monette et al. [13] found that the static elastic modulus (usually determined by the stress-strain curve obtained under compression according to BS 1881-5 [14]) of the concrete containing reactive aggregate stored in NaOH, strongly decreased from 28-days to 1 year. On the other hand, the dynamic elastic modulus showed only a slight decrease: in fact, the resonant frequency of the reactive concrete prisms increased during the first days of storage and dropped only later on. These results confirm the hypothesis of the progressive formation of new cracks which are continuously filled up by the swelling of either old or newly formed reaction products. As a matter of fact, the static modulus continuously decreases as it is strictly related to the compressive strength of the concrete while the dynamic modulus, due to the method of its evaluation based on the ultrasonic pulse velocity, is influenced by the presence and amount of voids and micro-cracks in the material. However, in this test method, it is not affected by the quality of the interfacial zone between cement paste and aggregate particles in which silica gel is more and more interposed during the development of the reaction. This fact supports the hypothesized mechanism, that causes the fluctuating trend of the dynamic elastic modulus detected on concrete cores stored in NaOH solution.

From figures 5 and 6 some information about the kinetics of the alkali-aggregate reaction can also be extrapolated: in fact, for each core the trend of the dynamic elastic modulus value changes after 50-60 days of storing, thus indicating the progressive filling up of the previous crack by swelling of reaction products and the subsequent generation of expansive pressure inside the concrete which leads to the opening of new cracks. Some experimental observations reported in [13] on concrete cores stored in the same condition, indicated that nearly the same time (60 days) was necessary for the development of cracks.

5 SUGGESTIONS FOR INTERVENTION

Firstly, it is necessary to assure the safety of the most deteriorated parts of the structure. In this regard, it is useful to know which of these parts are more deteriorated and the time remaining to take action in safe conditions without resorting to their total demolition. The intervention can be a partial substitution, or a simple restoration for the less serious cases. In each of these situations, a final protection from water is essential in order to avoid future problems.

As a matter of fact, an effective remedial measure for concrete structures affected by alkali-aggregate reactivity should limit the ingress of moisture into concrete while allowing water vapour to permeate out. In this way, water can be drained away from the structure rather than onto or through it and, consequently, the internal relative humidity inside it can be reduced. In fact, surface treatments with some silanes and siloxanes show beneficial effects in reducing deleterious expansion due to AAR, Fournier et al. [2], Salome et al. [15].

In practice, surface impregnation of the structural elements by silane and/or siloxane should be supported by some improvements in the drainage system in order to promote the progressive drying of the concrete and to avoid any possible ingress of water from the ground, from structural joints or from drainage.

On the other hand, the use of flexible waterproof membranes on the surface can be effective only when expansion and residual reactivity due to alkali-aggregate reaction is almost at an end, because it does not allow water vapour to permeate out and the moisture, which is present inside the structural element, is sufficient for promoting the reaction further.

If the severity of the damage does not require any short-term intervention, periodic inspections should be planned to monitor any ongoing deterioration.

In a recent work, Saint-Pierre et al. [10] focused their attention on the attenuation of ultrasonic waves through ASR damaged concrete and they concluded that systematic core drilling and attenuation measurements should be integrated into a maintenance program of a structure suffering from ASR and that a ranking of the damage extent would be then carried out.

6 CONCLUSIONS

On the basis of this experimental work, once AAR is diagnosed, it is necessary to take cores from the main structural elements of a damaged structure. The concrete cores can then be submitted to both the mechanical characterization and the accelerated laboratory test described above.

Therefore, the knowledge on the present state of the concrete together with its potential for further reaction can allow the prediction of the future development of concrete deterioration and it can be helpful for the management of the AAR damaged structure.

In relation to the bridge structures examined in detail, taking into account both the mechanical properties at the time of coring and the potential for future deterioration, evaluated by means of the accelerated laboratory test, the abutments and especially the piers seem to be the first in need of intervention.

On the other hand, for bearing blocks and girders the situation was not observed to be serious and a protection such as a surface treatment with some silane and siloxane could be enough for limiting moisture ingress and allowing water vapour to permeate out.

In the case of the actual piers and abutments, the prevention of the alkali-aggregate reaction by means of moisture reduction had to be accompanied by repairs and remedial works.

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Figure 1: Core (diameter 100 mm) extracted from a structure affected by AAR: it appears heavily cracked.

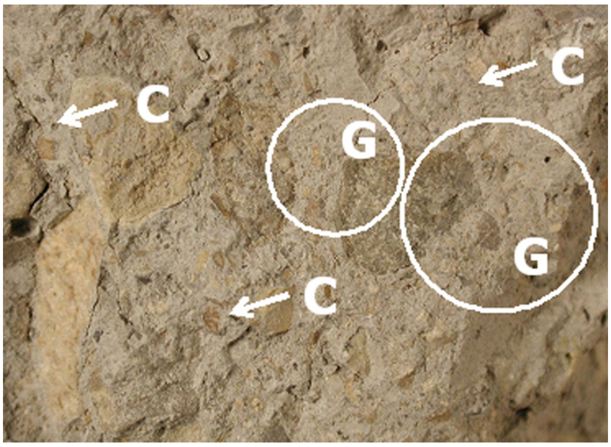

Figure 2: Magnification (5x) of the plane of detachment by optical microscope: the incipient formation of micro-cracks (C) and some glassy deposits (G) can be noticed.

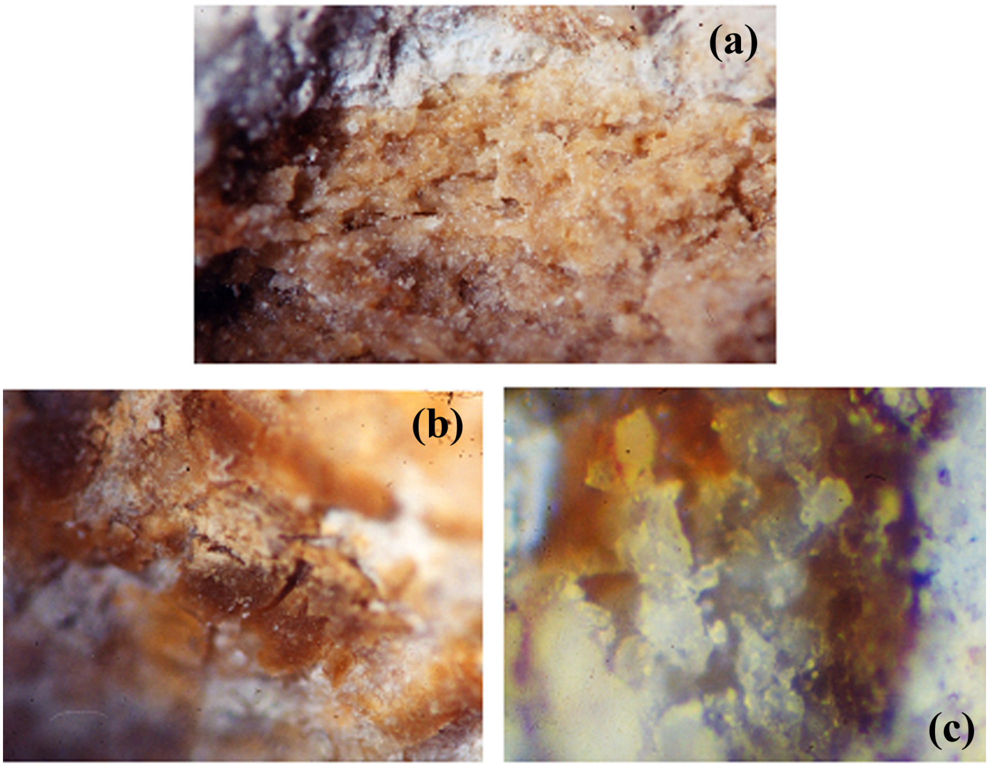

Figure 3: Images of a detachment plane by optical microscope at increasing magnifications: (a) 20x, (b) 50x, (c) 100x.

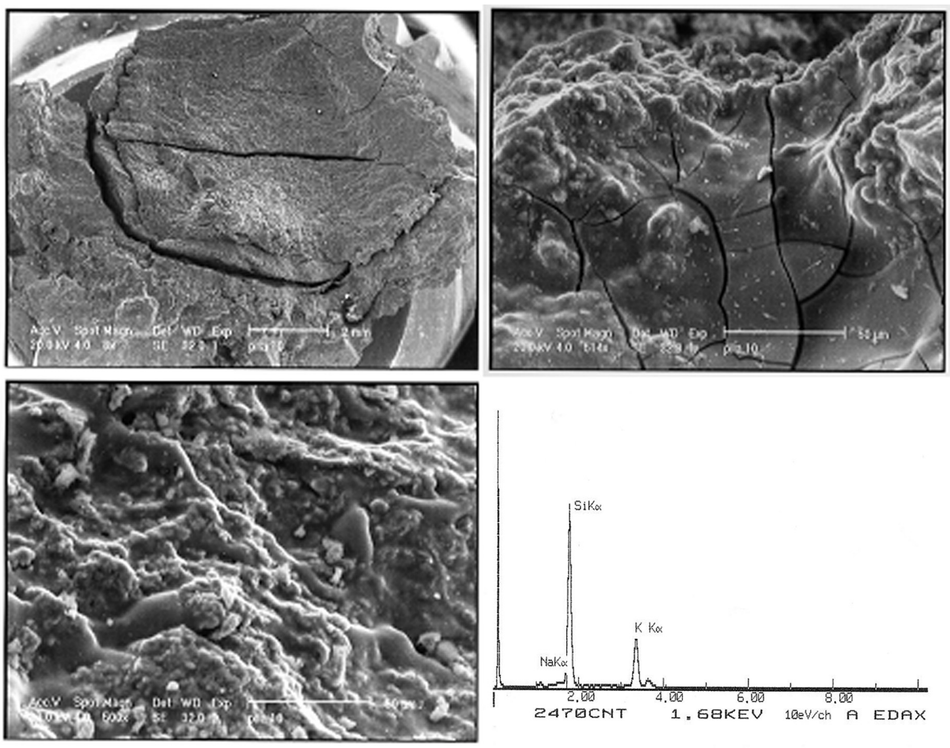

Figure 4: Some images obtained by scanning electron microscope (SEM) at increasing magnifications and relative energy dispersive x-ray analysis (EDXA).

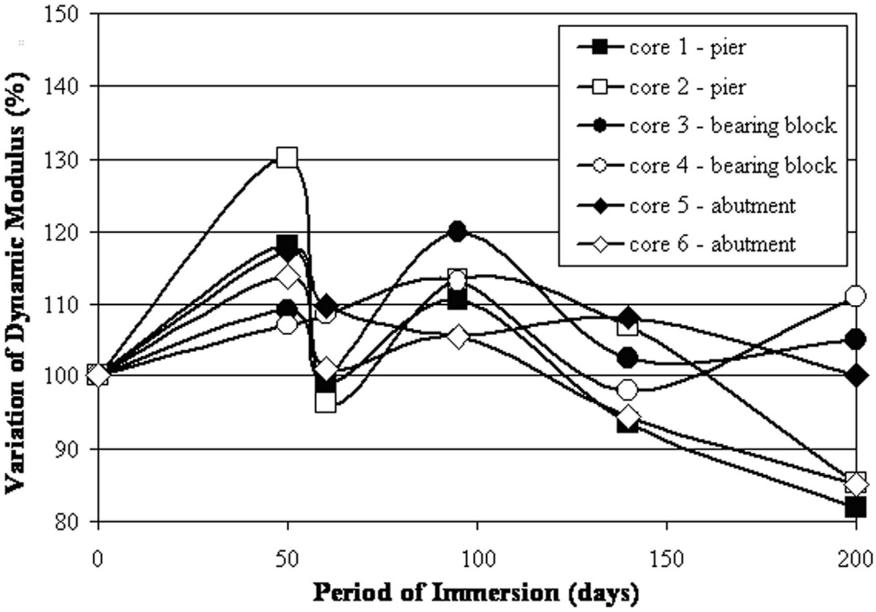

Figure 5: Variations in dynamic elastic modulus of the concrete cores for the first structure.

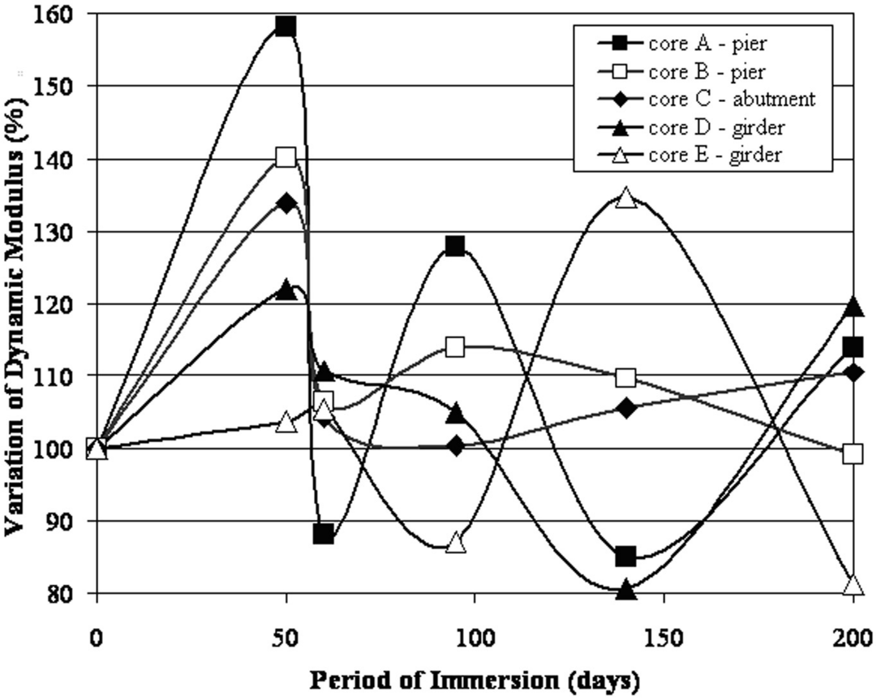

Figure 6: Variations in dynamic elastic modulus of the concrete cores for the second structure.