EVALUATION OF DAMAGE IN THE CONCRETE ELEMENTS OF THE VIADUCT "ROBERT-BOURASSA-CHAREST" AFTER NEARLY 50 YEARS IN SERVICE

Sanchez, L. [1]; Salva, P.[1]; Fournier, B.[1]; Jolin, M.[2]; Pouliot, N. [3]; Hovington, A.[3];

[1]Laval University, Geology and Geological Engineering Department, Quebec, QC, Canada
[2]Laval University, Civil Engineering Department, Quebec, QC, Canada [3] Quebec Department of Transportation, Quebec, QC, Canada

Abstract

The Robert-Bourassa-Charest viaduct (Quebec, Canada) has developed over the years clear symptoms of AAR-related damage. Several inspection surveys and analyses have confirmed that the coarse aggregate used in the construction (local siliceous limestone) was potentially alkali-reactive and for many years monitoring and laboratory tests were carried out on different elements of the structure. The demolition and replacement of the viaduct in 2010-2011 gave the opportunity for extracting and testing cores from different elements (concrete foundation blocks, columns and deck slab) of the structure, some of which had been repaired about 10 years ago using different approaches (sealers, polymer-based surface treatments and fiber-reinforced encapsulation). This paper presents the overall evaluation of the damaged elements of the viaduct through mechanical and microscopic tests, as well as in the visual inspections carried out prior to the demolition.

Keywords: stiffness damage test (SDT), assessment of damage, alkali-aggregate reaction.

1 INTRODUCTION

The Robert-Bourassa Charest viaduct is a highway bridge structure (Quebec, Canada) that was built in 1966 using an alkali-silica reactive limestone aggregate. The viaduct is made of a deck resting on reinforced concrete Y-shaped columns, themselves supported by massive concrete foundations. No specific information is available on the concrete mix designs; however, technical reports indicate that the 28-day design strengths for the concretes were 24 MPa for the foundations blocks and 28 MPa for the columns and decks [1].

Over the last three decades, many signs of distress developed on the various elements of the structure. Among them, one can find extensive steel corrosion and concrete delamination/spalling at the level of the deck (due to leaking joints), map cracking, scaling, disaggregation and pop-outs affecting the massive concrete foundations (due to the presence of alkali-reactive/frost-susceptible aggregates) and concrete spalling and steel corrosion on the columns and massive foundations exposed to salt-water spray from the traffic on the Robert-Bourassa highway [2]. Since the structural stability of the Y-shaped columns was one of the main source of concerns, mainly because of potentially high stresses levels in the stirrups, several columns were repaired about 10 years ago. Different repair approaches were carried out, including application of silane based sealers, conventional surface repair using commercially-available products (i.e. Masterseal 550, etc.), strengthening of the elements using reinforced concrete, non-reinforced, with/without lithium and composite materials [1].

2 ASSESSMENT OF DAMAGE IN THE DU-VALLON STRUCTURE

Over the years, many site inspection surveys, expansion monitoring and laboratory tests were performed on the Robert-Bourassa structure and cores extracted from its different structural elements. From the above investigations, Bérubé et al. [3] developed a guide for the diagnosis, prognosis and management of AAR-affected structures. This guide is based on a collection of laboratory tests (mechanical testing and petrography), such as the SDT (*Stiffness Damage Test*), DRI (*Damage Rating Index*), residual expansion, water soluble alkali, etc., and it aims at assessing the degree of deterioration of a concrete element/structure as well as its potential for further damage by AAR. Recent studies dealing with the tests proposed in the guide suggest that the SDT and the DRI are powerful tools for the diagnosis and prognosis of AAR in aging concrete structures. Nevertheless neither SDT nor DRI have a standard test procedure developed yet.

3 SCOPE OF WORK

In 2010, the Robert-Bourassa Charest south-structure was demolished and, prior to demolition, a visual inspection was carried out. The latter involved the measurement of crack opening and the determination of a visual rating of the Y-shaped columns. Cores were then extracted from foundation blocks and columns; the cores were wrapped in plastic film (to avoid humidity loss) and stored in the laboratory before testing.

This paper presents the results of the visual survey and of the testing of cores extracted from the foundations blocks and two Y-shaped columns (not treated-exposed/not exposed) of the structure (Table 1).

4 MATERIALS AND METHODS

4.1 Visual inspection

A visual inspection was carried out on two columns (not repaired- exposed and not exposed) and on the foundations blocks of the structure. Qualitative ratings were attributed according to their degree of damage.

4.2 Laboratory test methods

Stiffness Damage Test (SDT)

The concept of the Stiffness Damage Test (SDT) is to quantify the degree of damage in a concrete affected by AAR [4-6][1]. The method is based on a cyclic loading of concrete samples (cylinders or cores). The full procedure is described in Sanchez et al. [7] and the same parameters were adopted in this study.

Using a controlled loading rate of 0.15 MPa/s, five cycles of loading/unloading were applied on each set of samples. The latter was composed of three concrete cores extracted from the same structural element and with the same characteristics (geometry, degree of humidity, depth of surface, etc.) before testing.

- Samples from the foundation blocks: one of the goals of this part of the study was to verify the effect of the test loadings and the moisture condition of the samples on the results of the SDT. Three loadings were evaluated, i.e. 20%, 30% and 40% of the concrete mix-design strength. Specimens were generally stored in the moist curing room for 48 h prior to testing. Some cores were tested immediately after the above conditioning, while others were left to dry in the laboratory (unwrapped) for five weeks before testing. The cores left to dry were not replaced in the moisture curing room for 48h before testing.
- Samples from the columns: tests were carried out on cores from two columns, using loadings of 20% and 40% of the concrete mix-design strength.

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[1] "Damage" is generically defined here as the measurable harmful consequences of the various mechanisms (i.e. loadings, shrinkage, creep, AAR, DEF, freezing and thawing, etc.) on the mechanical properties, physical integrity and durability performance of a concrete.

Compressive strength

The compressive strength was carried out on the test specimens (from the foundation blocks or the columns) upon completion of the SDT. The aim was to verify the non-destructive character of the SDT for the loadings tested, as well as the validity of the compressive results measured after cyclic testing.

Damage Rating Index (DRI)

The concept of the DRI is to quantify the degree of damage in a concrete affected by AAR through petrographic analysis [8,9]. The procedure is described in Villeneuve & Fournier [10] and the same parameters were adopted in this study. The analysis (DRI) was carried out in two ways. First, the DRI was carried out on samples that were not subjected to SDT with the aim of verifying their microscopic degree of damage. Second, samples were analyzed by the DRI after having been subjected to the SDT (with different loadings), with the aim of verifying the non-destructive character of the SDT.

5 RESULTS

5.1 Visual inspection

Table 2 gives a summary of the visual rating of the two columns examined. The column 32 (exposed) suffered a very high degree of damage with generalized oriented and pattern cracking, and concrete disaggregation (Figure 1 A). Moderate-to-high degree of cracking is also observed on the column 43 (not exposed) despite being protected from direct moisture by the bridge deck (Figure 1 B). For the foundations block, the extent of damage ranged from very severe (extensive cracking, concrete corrosion and spalling, disaggregation, pop-outs) in the exposed portions to fair in the protected (under the deck) areas (Figure 1 C and 1D).

5.2 Stiffness damage test (SDT)

Foundation blocks

Figure 2 presents the responses of some SDT output parameters when the test is carried out with the three different loadings mentioned before. It is possible to see that the greater is the loading applied, the larger is the hysteresis area either for the first or the last four cycles. However, the values obtained in the first cycle were about three times larger than those corresponding to the average value of the last four cycles. A somewhat similar response was observed regarding the plastic deformation, although the differences observed in the results of the hysteresis area for the first cycle at 30% and 40% of the design load are quite similar (likely due to high variability between test specimens). The results of the modulus of elasticity as the average of the cycles II and III were the opposite of the plastic deformation (as expected). In the same way, the results of 30% and 40% were switched, and the damage variability of a heterogeneous material could likely explain this fact. The values of plastic deformation and modulus of elasticity for the last four cycles do not seem to be useful as the values were quite arbitrary (mainly for the plastic deformation).

Figure 2 also illustrates the effect of drying on the output responses in the SDT (for a loading applied of 30% of the concrete mix- design strength). The moisture "history" of the test specimen is a critical parameter as specimens subjected to an extended drying period prior to testing show a significant increase in stiffness (and modulus of elasticity) and therefore decreased hysteresis area and plastic deformation throughout the test (for the first and last cycles).

Columns

Figure 3 presents the responses of some SDT output parameters when the test is carried out with two different loadings (20% and 40%) on the cores extracted from the columns 32 (exposed to excessive moisture) and 43 (exposed to environment but protected from direct moisture). Once again, the greater is the loading applied, the larger is the hysteresis area, either for the first or the last four cycles. The values obtained in the first cycle were about two times larger than those corresponding to the average value of the last four cycles. These differences are however lower for the columns than for the foundation blocks. As the level of damage in the foundation blocks is greater than for the columns, it seems that using data from the first cycle hysteresis in the SDT test method becomes more critical as the degree of damage increases in the concrete.

The responses of the test regarding the plastic deformation over the five cycles were almost the same as the hysteresis area, although the result obtained at the 20% loading for the column 32 was unexpected. It thus seem that for this parameter, as for the hysteresis, the use of 40% of the concrete mix-design strength as the loading test condition gives a better indication of the degree of damage of a concrete core. As for the cores from the foundation block, the values of plastic deformation when the average of the last four cycles is used, do not seem to be useful as they were quite arbitrary. The values of modulus of elasticity, as the average value of the cycles II and III or the average value of the last four cycles provided similar outputs for both loadings. Based on the outputs of the SDT, the internal damage in the non exposed (or protected) column 43 seems more important than that of the column 32. This may be surprising at first sight; however, the visual survey of the columns revealed significant cracking in the column 43 (Figure 1 D).

5.3 Compressive strength

Foundation blocks

The results of compressive strength testing for the cores extracted from the foundation blocks indicated a difference between cores previously tested at 20% and 30/40% of the concrete mix-design strength in the SDT (Table 3). This suggests that the use of loadings greater than 20% of the concrete mix-design strength may have introduced new cracks in the above concrete, thus decreasing its compressive strength. However, to confirm these results, petrographic analysis should be carried out to verify whether the amount of cracking changed for cores tested with loadings greater than 20% in the SDT.

Columns

The compressive strengths of the cores extracted from the columns, unlike those obtained on cores from the foundation blocks, did not present significant difference between 20% or 40% of the concrete mix-design strength (**Table 3**). However, the degree of damage in the column cores, based on the SDT results, is significantly lower than that in the foundation blocks cores. So, this suggests that the degree of damage may likely influence the maximum stress that could be applied on a sample in the SDT for not introducing new cracks. On the other hand, this hypothesis was not seen by the authors for laboratory samples incorporating highly-reactive aggregates and that had suffered from ASR up to an expansion of about 0.30% [7].

5.4 **Damage rating index (DRI)**

Foundation blocks

The DRI results for the cores extracted from the foundation blocks, when the SDT was not carried out on them, showed a high degree of damage (values of about 800-850) (Figure 4). One could see many white veinlets within the aggregate particles and some cracks in the paste filled with reaction products of AAR. When cores from the same element were analyzed after having been subjected to the SDT (with loadings from 20% up to 40% of the mix-design strength), the results were similar, i.e. within the variability of the test (Figure 4). Therefore, this suggests that the use of loadings up to 40% of the concrete mix-design did not introduce new cracks in the samples, at least in the scale of the microscopic analysis used in the DRI (16X magnification). This suggests that the decrease in the compressive strength for the samples tested at 30% and 40% of the concrete design strength could be attributed to the variability of a heterogeneous (and highly deteriorated) material rather than to an introduction of additional cracking due the SDT.

Columns

The samples presented a lower degree of damage (DRIs of 270 to 350) in comparison with those from the foundation blocks (DRIs of ≥ 800) (Figure 4). The cores from the non exposed column 43 presented a greater degree of damage than the ones from the exposed column 32. These results would seem surprising at first sight; however, they go in the same direction as those obtained in the SDT (section 5.2) and from the visual survey of the element, which show significant cracking in the column 43.

6 DISCUSSION

Regarding the effect of the loading level used in the SDT procedure, one could see that the greater is the loading, the greater is the hysteresis area provided by the samples in the test. However, the use of 40% of the mix design strength as the preferred loading seems to be the best choice since the responses between deteriorated and non (or less) deteriorated concrete elements are clearer, the parameters analyzed (hysteresis area, plastic deformation and the modulus of elasticity) generally demonstrated coherent behavior (within the inherent variability observed within a set of damaged cores), and that loading level is not introducing additional damage/cracking in the concrete specimens investigated (confirmed by petrography). These above results obtained on field specimens confirm those of tests carried out on ASR-affected laboratory test specimens [7].

Similarly, it seems largely preferable to use the first cycle with either the hysteresis area or the plastic deformation as the output parameters for the test. It looks like rejecting data from the first cycle, as originally proposed by Crisp et al. [4, 5] will result in loosing important information regarding the extent of damage in the test specimens that could not be recovered in the following cycles. This loss of information is even more critical for test specimens with superior degrees of damage. It is also quite important that a standard procedure for the SDT method be developed because one could see that some test parameters, such as the moisture history of the test specimens, could really influence the responses of the test.

Adopting 40% as the test loading in the SDT, one could visualize that the foundation blocks presented a higher degree of damage than the columns. These results were confirmed through petrographic analysis. Regarding the columns analysis, it was quite surprising, at first sight, to see more internal damage in the column 43 (not exposed) compared to the column 32 (direct exposure to the environment). The visual survey of the above columns indicated a larger overall deterioration for the exposed column 32, in good part due to the effects of freezing and thawing cycles. However, significant cracking was also observed in the column 43. It does seem that the surface appearance and the visual rating attributed before further testing on cores could sometimes provide a misleading indication of the internal distress in aging concrete elements. The real bulk degree of damage can indeed vary according to the depth of the core evaluated, especially in the case of reinforced concrete elements. In this case, analyses from both physical testing and microscopic evaluation resulted in the same diagnostic, which increases that reliability of the responses found.

Even though the compressive strength results obtained for the cores of both columns and the foundation blocks were considered satisfactory, further works are needed to validate the use of the compression test on cores after being subjected to SDT.

7 CONCLUSIONS

After carrying out physical and microscopic tests on cores extracted from either the foundation blocks or the columns of a 50-year old bridge structure (Robert-Bourassa Charest) affected by ASR, one can conclude that:

- The SDT carried out up to a 40% of the mix-design strength still maintain a non destructive character. It seems this loading represents the best choice to carry out the test;

- The hysteresis area of the first cycle, the plastic deformation over the 5 cycles and the average value of the 2nd and 3rd cycles of the modulus of elasticity seem to be the best output responses in the test;
- Care should be taken in the SDT test procedure (i.e. moisture condition/history of the samples, etc.) since these parameters can really influence the test responses;
- The cores from the foundation blocks demonstrated greater damage than those from the reinforced concrete columns (both exposed or not). This was confirmed by physical and microscopic evaluations;
- The surface cracking that gave rise to the application of damage ratings did not represent the real bulk degree of damage of the columns. Either SDT or DRI confirmed these responses;

8 REFERENCES

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Table 1. Tests methods carried out through the assessment of the structure.

Element	Qualitative visual inspection	SDT Carried out on cores of: 100 mm in diameter x 200 mm long	DRI Carried out on cores of: 100 mm in diameter x 200 mm long
Columns	Two columns (not treated - exposed and not exposed). Visual Rating attributed.	• 6 cores from each column were tested. • Testing carried out at two	2 cores from each column were analyzed (200 cm² for each column)

		loading levels (20% and 40% of the concrete mix-design strength).	
Foundation blocks	Carried out on the element. Visual rating not attributed.	• 12 cores were tested. • Testing carried out at three loading levels (20%, 30% and 40% of the concrete mix-design strength) • Testing carried out to evaluate the effect of drying samples before testing.	4 cores of the element were analyzed (400 cm²)

Table 2. Visual signs of distress of the untreated columns inspected.

N°	Place	Max. Average crack opening (mm)	Rating
32	Exposed	0.60	5
43	Not-exposed	0.50	3-4

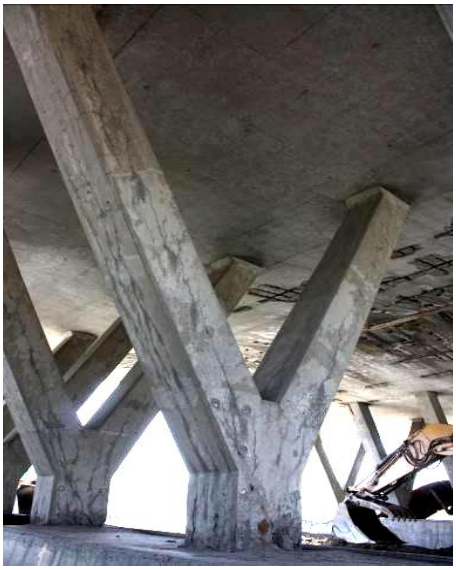
Rating: 0 – Not damaged; 1- very slightly damage; 2- damaged, but overall slightly; 3- fairly damaged; 4- high damage; 5- very high damage.

Table 3. Compressive strength for all the cores tested.

Compressive strength (MPa)	**Foundation Blocks**			**Columns**			
				32		**43**	
	20%	30%	40%	20%	40%	20%	40%
	23	17	17	42	47	38	39

A

B

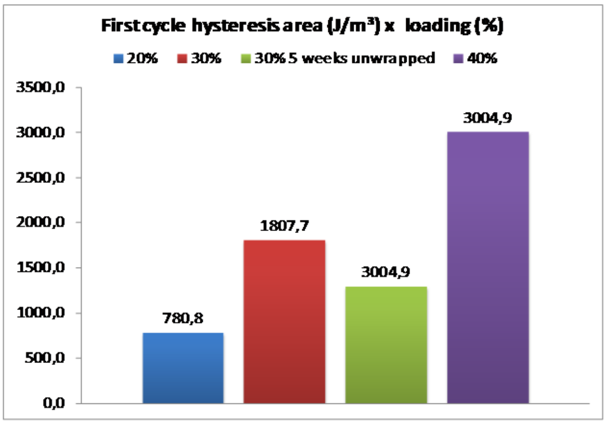


C

D

Figure 1. Robert-Bourassa-Charest concrete elements: A. Concrete column 32 (exposed). B. Concrete column 43 (not-exposed). C, D. foundation blocks.

A



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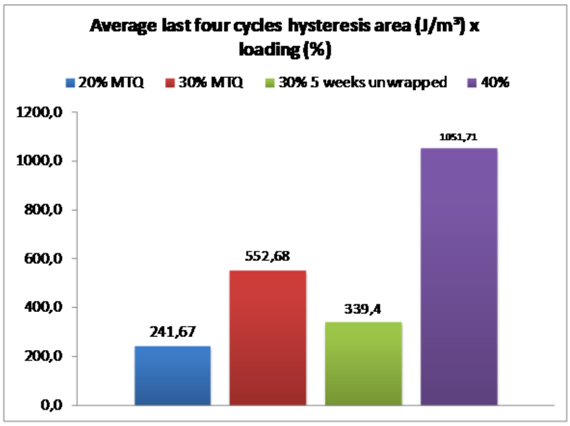

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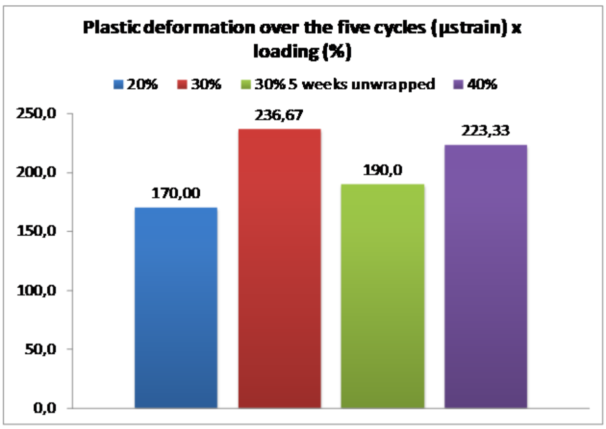

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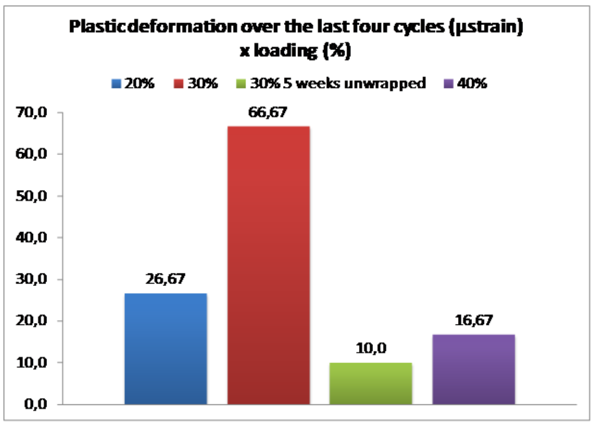

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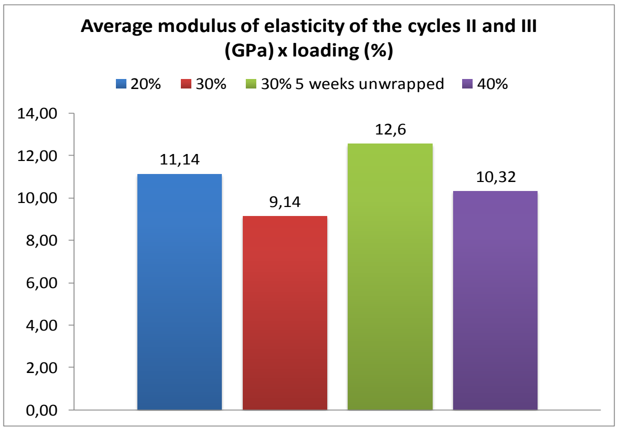

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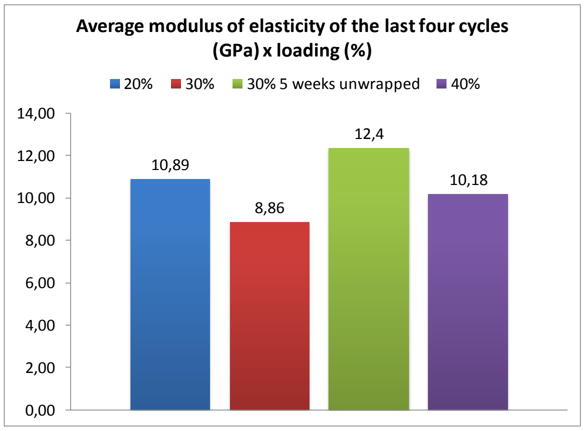
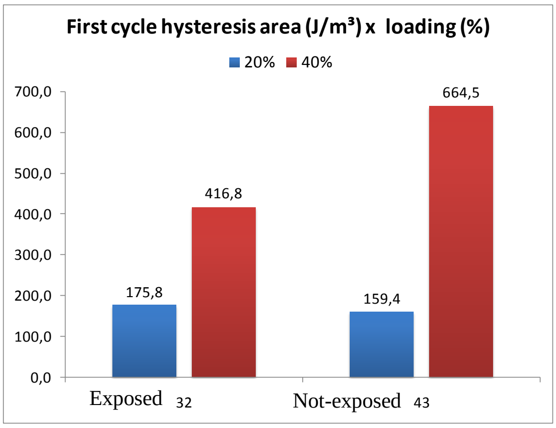


Figure 2. Responses of some SDT output parameters versus the loading applied (% of the concrete strength) for the cores from the foundation blocks.

A



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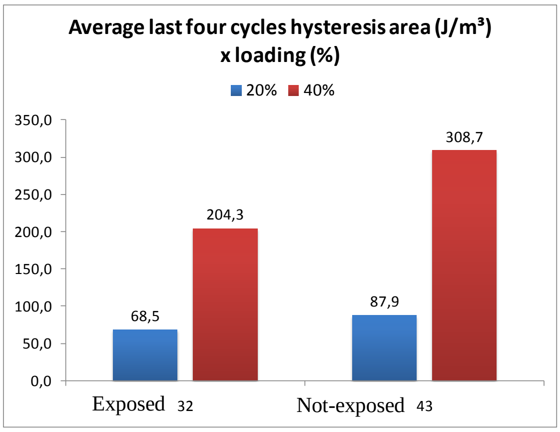
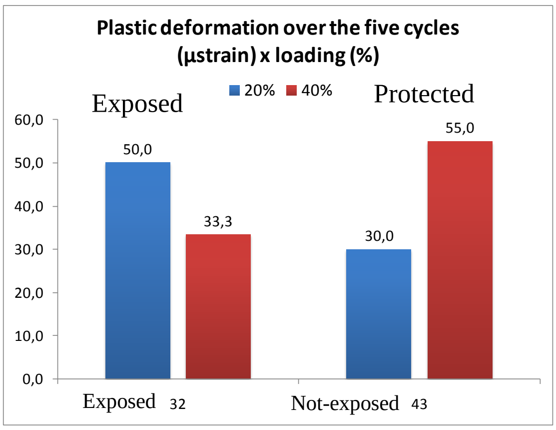


C



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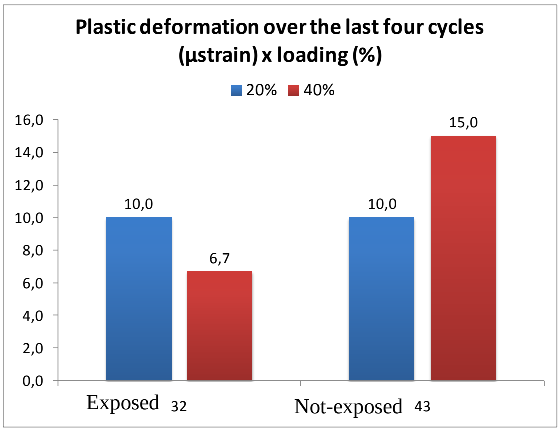

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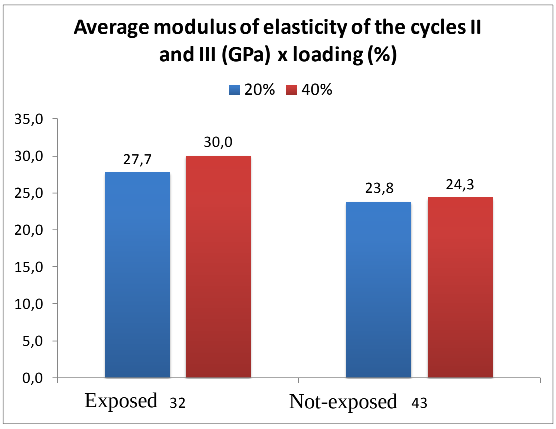

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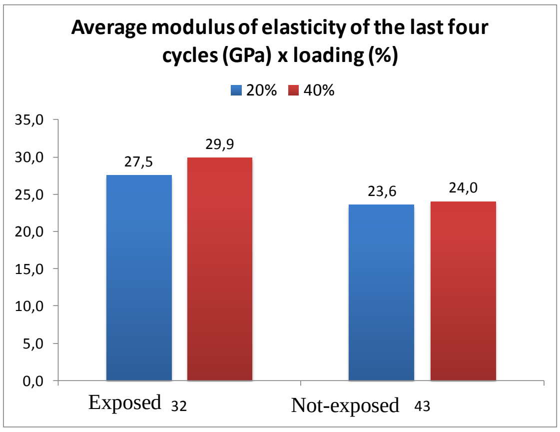
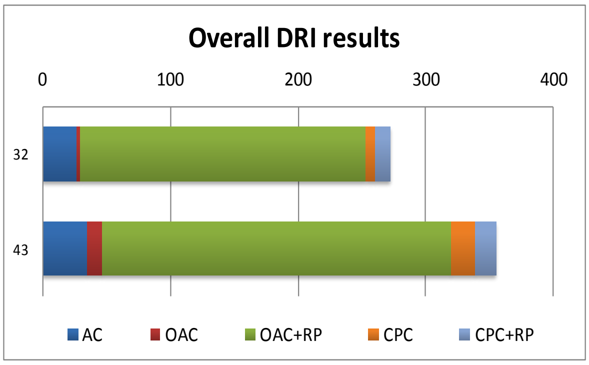


Figure 3. Responses of some SDT output parameters over the different loadings applied (20% and 40% of the concrete mix-design strength) for the two columns studied.

A



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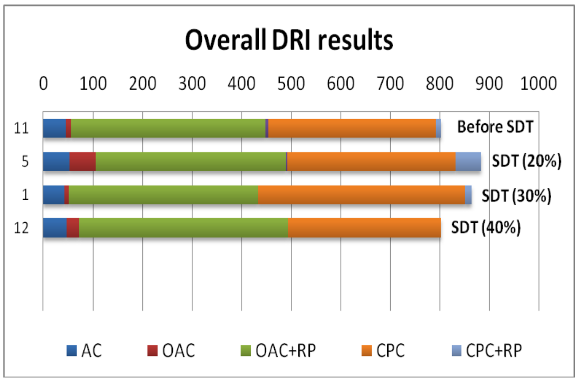

AC – aggregates cracking; OAC – open aggregates cracking; OAC + RP - open aggregates cracking with reaction products; CPC- cement paste cracking; CPC + RP - cement paste cracking; with reaction products.

Figure 4. Overall DRI results for the columns (A) and foundation blocks (B).