CRITICAL PARAMETERS OF THE STIFFNESS DAMAGE TEST FOR ASSESSING CONCRETE DAMAGE DUE TO ALKALI-SILICA REACTION

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Abstract

The Stiffness Damage Test (SDT) is a powerful tool that can be used for assessing the degree of damage in concrete affected by ASR. This paper presents the results of the evaluation of the effect of various parameters on the efficacy of the SDT. These analyses were carried out on two types of concrete (25 and 35 MPa) and two types of reactive aggregates. The diagnostic character of the various output parameters were analyzed against the expansion of the concrete specimens and the results showed that the SDT should be carried out with a percentage of the design strength (ideally 40%) instead of working with a fixed loading, as previously suggested in the literature. Parameters such as the hysteresis of the first loading/unloading cycle, the average modulus of elasticity of the second and the third cycles, as well as the plastic deformation during the test seem to give good correlations with the amount of expansion reached by the concrete.

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

1 ASSESSMENT OF DAMAGE IN CONCRETES DAMAGED BY AAR

First of all, the word “damage” is defined in this work as the harmful consequences (measurable ones) of various types of mechanisms (e.g. loadings, shrinkage, creep, ASR, DEF, freezing and thawing, etc.) on the mechanical properties, physical integrity and durability of a concrete element. It is well-established that different deleterious mechanisms affecting the long-term durability of concrete generate different patterns of internal damage whose "signatures" were diagrammed by St-John et al. [1]. However, one of the biggest challenges in engineering is to establish the correlation between the above "signatures" and the loss in mechanical properties and durability of the material. Many petrographic methods were developed with this aim but almost all the analyses carried out were described in a qualitative (and narrative) way. Therefore, petrographic analysis is often criticized by engineers as they look for a precise evaluation on the extent of damage of a concrete element [2]. Recent studies dealing with the mechanical responses of damaged materials suggest that the “Stiffness Damage Test (SDT)” could provide a diagnostic evaluation of the damage in concrete due to ASR. Nevertheless, the SDT does not have a standard test procedure so far, and an in-depth evaluation on the input and output parameters of the test should be done for its correct use.

2 STIFFNESS DAMAGE TEST (SDT)

The concept of the SDT is to quantify the degree of damage in concrete damaged by ASR [3,4]. The test method was developed by Walsh et al. (1965) [5] as they observed a good correlation between the cracks density and the cycles of loading/unloading (stress/strain) of rocks. Crouch et al. (1987) [7], following those results, proposed the new test (SDT) for concrete samples. The method is based on the cyclic loading (in compression) of concrete cylinders or cores (diameters > 70 mm; length / diameter of 2.5 – 2.75) [3]. Initially, the SDT involved the application of a stress of 5.5 MPa (rate of 0.1 MPa/s) and was repeated five times [4,5]. The authors carried out more than 1000 tests with cores extracted from damaged concrete structures and they proposed the following parameters as the diagnostic parameters of the test [3]:

- Modulus of elasticity (Ec): average modulus of elasticity value of the last four cycles);

- Hysteresis area (H - J/m^3): average hysteresis area of the last four cycles;
- Non linearity index (NLI): ratio between Ec and the modulus of elasticity taken on the half of the slope of the stress applied. This parameter provided informations about the crack patterns of the samples.

Crisp et al. [3,4] found that the hysteresis area of the first cycle was greater than that of the following cycles and attributed the above behavior to sliding across surfaces of the open cracks. Therefore, they decided to reject the results corresponding to the first cycle. According to Crisp et al. [4], the modulus of elasticity is the most sensitive parameter of the test for slightly damaged concretes. However, for higher degrees of damage, the hysteresis area is the critical parameter for detecting deterioration. Also, the authors found that samples with a main cracking pattern perpendicular to loading result in a low modulus of elasticity, high hysteresis area and NLI greater than unity, while those with a main cracking pattern parallel to loading are recognized with a high modulus of elasticity, low hysteresis area and NLI lower than unity. However, Crisp et al [4] did not provide any information about the aggregate types or the mix-designs used in their work.

Smaoui et al. [8] continued studying the SDT on laboratory concrete samples incorporating a variety of reactive rock types and that had reached differents expansion levels (stored at 38°C at 100% R.H.). After carrying out many tests, the authors found that the best output response for the SDT was the hysteresis area of the first cycle for test specimens loaded at the 10 MPa level; lower stresses did not offer the capacity of diagnosing the degree of damage in the concrete due to ASR. The authors also evaluated other parameters of the test, including plastic deformation during loading/unloading cycles, and they found that the correlation between the expansion and plastic deformation was also fairly satisfactory. They however noted significant variations for either the hysteresis area or the plastic deformation for concretes incorporating different types of reactive aggregates. These differences were possibly associated to the nature of the aggregate (fine or coarse) and differences in the internal pattern of damage, as they can generate their own mode of reaction (i.e. pattern/density/orientation of cracking depending on whether the damage is generated in the fine or coarse aggregate, or by different rock types, etc.). Based on their findings, Smaoui et al. [8] proposed the following parameters as the best responses of the test: 1) hysteresis area of the first cycle (J/m^3) and 2) plastic deformation accumulated during the five cycles of loading/unloading (ustrains).

The work of Smaoui et al. [7] was based on one single concrete mix-design (420 kg/m^3), and a fixed 10 MPa loading value. It is logical to believe that using a single load of 10 MPa could result in different responses in the SDT, depending on the type of concrete analyzed (i.e. ≠ mix-designs, ≠ types of fine/coarse aggregate, etc.). However, this information has not been studied deeply yet. Without this information, the analysis of the SDT for different mix-designs could result into erroneous estimates of the level of damage and the expansion achieved to date. Also, the SDT was developed to assess the effects of ASR on concrete; however, the test certainly has the potential of assessing damage from other mechanisms (e.g. freezing and thawing, action of fire, impact loads, DEF, etc.) [4]. Smaoui et al. [7] also reported a good correlation between the expansion to date of a concrete due to freezing-thawing cycles and the hysteresis area of the first cycle in the SDT. However, there is currently no data recognizing the signature of a damage mechanism over another when tested in the SDT. Finally, the SDT has the characteristic of being non-destructive, so if the number of samples taken within the structures is limited (for economic reasons), we can consider using the same cores for other tests, such as residual expansion, petrographic tests, compressive and tensile strengths, etc. [4].

3 SCOPE OF WORK

As indicated in the previous section, the lack of a thorough study on the input/output parameters of the SDT could lead to erroneous interpretation of the test results. Among all of the parameters of the test, the most important ones are as follows:

- Input parameters: test loading (versus concrete mixture designs);
- Output parameters: analysis of hysteresis area (1st cycle vs last four cycles), modulus of elasticity (1st cycle vs average for cycles 2 and 3) and plastic deformation (over the 5 cycles) of the damaged concretes.

This paper presents the evaluation of these parameters on the responses in the SDT.

4 MATERIALS AND METHODS

4.1 Materials and mixture proportions

The analyses were carried out with two types of concrete (25 MPa and 35 MPa) and two highly-reactive aggregates (New Mexico gravel and Texas sand)[1]. The concretes were designed to contain the same volume of paste and the same volume of aggregates (i.e. from one mix to another), so one can compare similar systems (**Error! Reference source not found.**). A total of 56 samples (100 x 200 mm cylinders) were cast from each of the mixtures. **Error! Reference source not found.** presents the testing matrix carried out. After casting, the specimens were cured for 48h in a moist curing room (23°C) and then stored at 38°C and 100% R.H. until they reach the expansion levels selected (0.05%, 0.12%, 0.20% & 0.30%). When they reached the above expansion levels, the specimens were wrapped in plastic film and stored at 12°C until testing (because of testing capacity issues). Even though they were wrapped, the specimens were restored for 48h in the moist curing room before stiffness damage testing in order to follow the procedure proposed for concrete cores extracted from real structures (A23.2-14C).

4.2 Methods for assessment and analysis

Stiffness Damage Test (SDT)

The test samples were subjected to five cycles of loading/unloading at a controlled loading rate of 0.15 MPa/s. One set of samples was composed of twelve concrete cylinders with the same mix-design, type of aggregate and expansion level. Each set of samples was divided into 4 sub-sets of three cylinders, in order to evaluate four different loading levels through the test, i.e. 15%, 20%, 30% and 40% of the design (28-day) concrete strength). All the results presented here are the average values of three specimens (sub-sets) tested.

Damage Rating Index (DRI)

The semi-quantitative petrographic analysis of the concrete specimens, using the DRI method [9] and recently modified by researchers from the Laval University [10], was carried out in two ways. First, the DRI was performed on a polished sample that was not subjected to SDT, for determining the degree of damage in the sample at each selected expansion level. Second, one sample of each sub-set mentioned before was cut and polished, after completion of the SDT (40% load), to verify the non-destructive character of the SDT.

5 RESULTS

5.1 Stiffness Damage Test (SDT)

Figure 1 presents the results of the most critical SDT parameters, for tests carried out at the four different loading levels and four expansion levels (up to 0.30%) on the 25 MPa concretes incorporating the reactive Texas sand. **Figure 2** illustrates the same parameters for three expansion levels (up to 0.20%) of the 25 MPa concrete incorporating the reactive New Mexico gravel. For both aggregates tested in the 25 MPa concrete, the data show that the SDT is not fully «diagnostic» for loads up to 30% of the concrete mix-design

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[1] The 14-day accelerated mortar bar expansions for the Texas sand and the New Mexico gravel are 0.995% and 1.114%, respectively [8]. The reactive sand (Jobe) and gravel (New Mexico) were used in combination with non-reactive coarse (pure limestone) and fine (granitic) aggregates, respectively.

strength, as one cannot see clear differences in the responses with increasing expansion in the test specimens. However, at a load corresponding to 40% of the design concrete strength, the test better highlights the differences in the damage as a function of expansion; this can be seen either by the measurements of the hysteresis area (first cycle or average value of the last four cycles) or of the plastic deformation of the test specimens (five cycles or average value of the last four cycles). The modulus of elasticity for both mixtures was found to decrease as a function of the expansion level, as expected.

Figure 3 and **Figure 4** present the same parameters as analyzed before, but this time for the 35 MPa concretes. Their behavior is basically similar to that obtained for the 25 MPa concretes, i.e. the use of a 40% load level better highlights the differences between the expansion levels of the samples, either by measuring the hysteresis area (first cycle or average value of the last four cycles) or the plastic deformation (first cycle or average of the last four cycles). As observed for the 25 MPa concretes, the modulus of elasticity of both 35 MPa concretes was found to decrease with increasing expansion, as expected.

5.2 Damage Rating Index (DRI)

Error! Reference source not found. shows the results of the petrographic analysis performed on the 25 MPa specimens incorporating the Texas sand and New Mexico gravel, before and after the SDT test (40%). One can see that the DRI values are similar from one set to another, which suggests that carrying out the SDT up to 40% of the concrete design strength does not introduce additional damage into the sample analysed, at least at the magnification used in the test (16X). This is true for both aggregates investigated.

6 DISCUSSION

In this study, the SDT were carried out with loading levels ranging from 15 to 40% of the 28-day concrete mix-design strength. The maximum loading (40%) was chosen as one knows that loadings above and beyond this value can introduce new cracks in the sample tested in compression [11]. However, almost all the data available for SDT carried out on ASR-affected concretes were obtained with fixed loading values of either 5.5 MPa [3,4] or 10 MPa [7], even though one could think this is not mechanistically appropriate to analyse concretes with different mix-design strengths in such a way. Table 4 shows that when fixed loading values are used for the SDT, one could easily misinterpret the response of the test, for example based on the hysteresis area values measured. As demonstrated previously, it seems the best loading to apply in the SDT is 40% of the concrete mix-design strength, as it provides a good diagnosis of the expansion degree of the damaged material and still maintains a non destructive character, thus allowing other tests like microscopic analysis or compressive strength determination to be carried out on the same specimens, if needed or desired.

Regarding the output parameters in the test, one recognizes that the hysteresis area, the modulus of elasticity and the plastic deformation are very important responses of the damaged concretes under cyclic loading. But there is a question that still remains: must one use the values measured for first cycle or the average values of the last four cycles? To answer this question, one needs to analyze each parameter separately. The hysteresis area of a damaged sample corresponds to the energy used to close its disseminated cracks during a compressive test. The results obtained in this study indicate that the hysteresis area values for the first cycle are 2 to 3 times greater than the average ones for the last four cycles. Even though both situations could be used for evaluating the damage level in concrete affected by ASR (at the 40% load level) (see Figures 1 to 4), eliminating the response obtained during the first cycle may result in losing important information about the extent of cracking in the test specimens. So, for this parameter, the results obtained for the first cycle would be more interesting. On the other hand, the plastic deformation in cyclic testing is a parameter that could distinguish damaged materials better as the numbers of cycles are increased. So, it is logical to think that the analyses of the plastic deformation over the five cycles of the test could be more diagnostic. Finally, since the five cycles of the SDT will be carried out at 40% of the concrete mix design strength, it is logical that the same parameters commonly used for the ordinary modulus of elasticity determination are maintained. Therefore, the use of the average value of the cycles II and III could be used as the responses of this output parameter in the test. Globally, carrying out the SDT with the above procedure introduces a lot of additional and useful information (hysteresis areas and plastic deformation) to the conventional modulus of elasticity test. The **Figure 5** shows the evaluation of the parameters mentioned above on the concretes studied in this work. The test provides a good diagnosis of the degree of expansion for all mixtures with either the Texas sand or the New Mexico gravel (correlation coefficients > 0.84 for all the parameters analyzed).

7 CONCLUSIONS

Input and output parameters of the Stiffness Damage test (SDT) were discussed for tests carried out using 25 MPa and 35 MPa concrete mixtures incorporating two types of reactive aggregates (Texas sand and New Mexico gravel). The main conclusions are:

- The SDT should be carried out with a percentage of the mix-design strength instead of a fixed loading to analyse damage in different types of concretes;
- The hysteresis area of the first cycle, the plastic deformation over five cycles and the average value of the modulus of elasticity obtained in second and third cycles seem to be the best parameters to use as output responses in the test;
- Even using 40% of the concrete mix-design strength, the test seems to maintain its "non-destructive" character (as one could see from the microscopic tests).
- The SDT seems to be a powerful tool but more tests are required with a greater number of samples (different mix-designs and reactive aggregates) to confirm its efficiency;
- After carrying out the test with more samples, a better correlation between the values of the hysteresis area and the plastic deformation should be established as a quantitative assessment of the damage in concrete samples.
- The SDT could be used for other deleterious mechanisms, such as DEF, freezing and thawing; however, an in-depth study is required.

8 REFERENCES

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Table 1. Concrete mix-designs used.

25 MPa	Materials (kg/m^3) Mixture - Texas sand	Materials (kg/m^3) Mixture - New Mexico gravel	Materials (L) Mixture - Texas sand	Materials (L) Mixture - New Mexico gravel
Cement	314.0	314.0	101.0	101.0
Sand	790.0	714.0	304.0	264.0
Coarse aggregate	1029.0	1073.0	384.0	424.0
Water	192.0	192.0	192.0	192.0
Air (%)	0.0	0.0	20.0	20.0
35 MPa	Materials (kg/m^3) Mixture - Texas sand	Materials (kg/m^3) Mixture - New Mexico gravel	Materials (L) Mixture - Texas sand	Materials (L) Mixture - New Mexico gravel
Cement	370.0	370.0	118.0	118.0
Sand	790.0	714.0	304.0	264.0
Coarse aggregate	1029.0	1073.0	384.0	424.0
Water	174.0	174.0	174.0	174.0
Air (%)	0.0	0.0	20.0	20.0

Table 2. Testing matrix.

Tests		Number of samples by degree of expansion				Total	
		0,05%	0,12%	0,20%	0,30%		
Stiffness Damage Test; % of the concrete mix-design strength	15%	3	3	3	3	12	
	20%	3	3	3	3	12	
	30%	3	3	3	3	12	
	40%	3	3	3	3	12	
Damage Rating Index		2	2	2	2	8	56

Table 3. Microscopic analysis (over the DRI) of the 25 MPa mixtures with the Texas sand and the New Mexico gravel for different degrees of expansion.

Tests		Expansion degrees for all the 25 MPa mixtures						
		0,05% 25 MPa Texas sand	0,05% 25 MPa NM gravel	0,12% 25 MPa Texas sand	0,12% 25 MPa NM gravel	0,20% 25 MPa Texas sand	0,20% 25 MPa NM gravel	0,30% 25 MPa Texas sand
DRI values	Standard (without SDT)	237	254	348	380	560	602	715
	SDT 40% + DRI	249	237	360	358	536	599	739

Table 4. Comparison between fixed and percentages of mix-designs loadings.

(%)	fck MPa	Loading (MPa)	Expansion (%)	Hysteresis area (J/m³) - Texas sand	Hysteresis area (J/m³) - New Mexico gravel
40%	25	10	0.12	1142	1883
30%	35	10.5	0.12	691	623
40%	25	10	0.20	1802	2213
30%	35	10.5	0.20	897	913

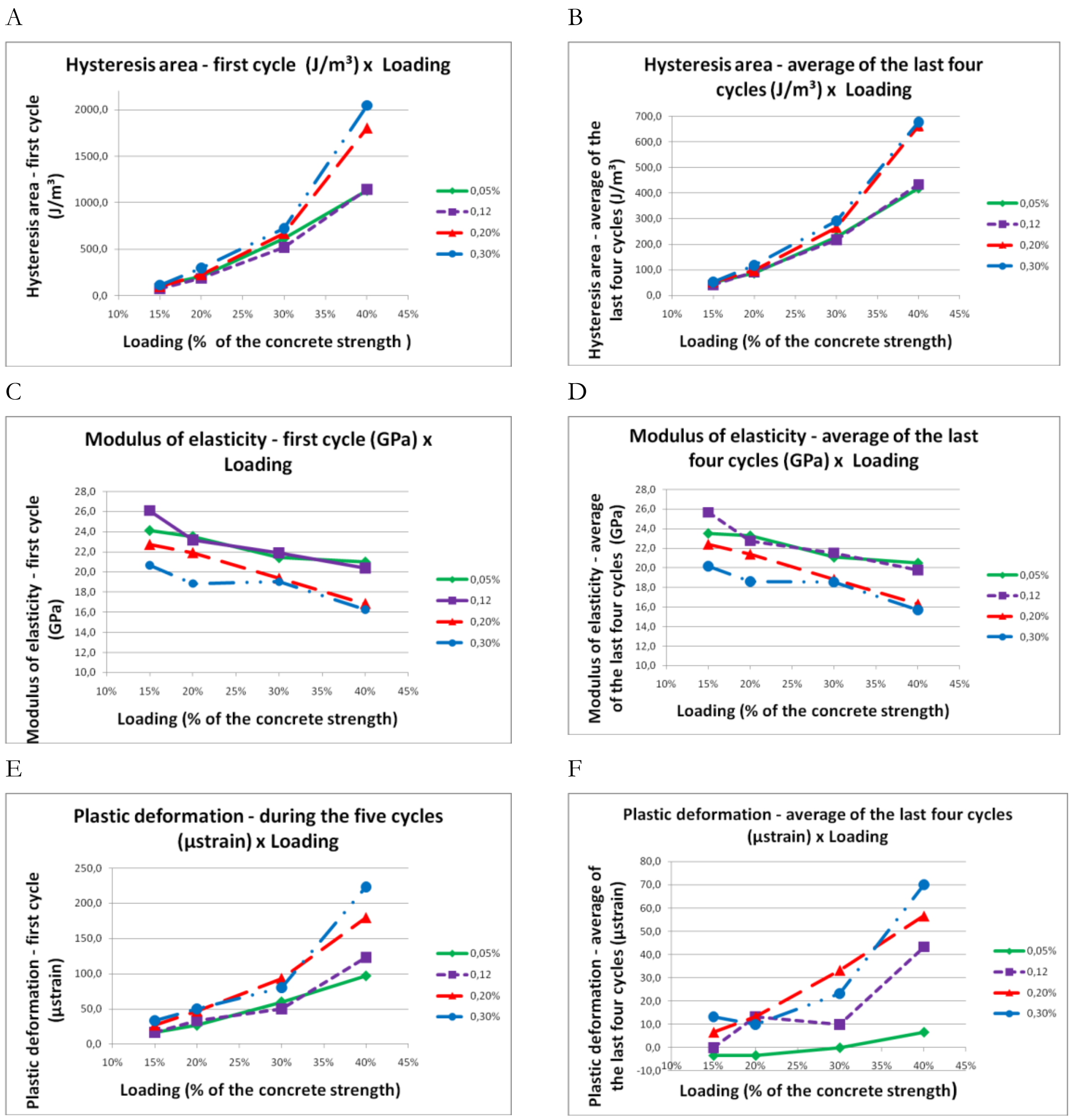


Figure 1. SDT output parameters versus applied loading (% of the concrete strength) for a 25 MPa mixture with a reactive (Texas) sand. A,B Hysteresis area. C,D Modulus of elasticity. E,F Plastic deformation.

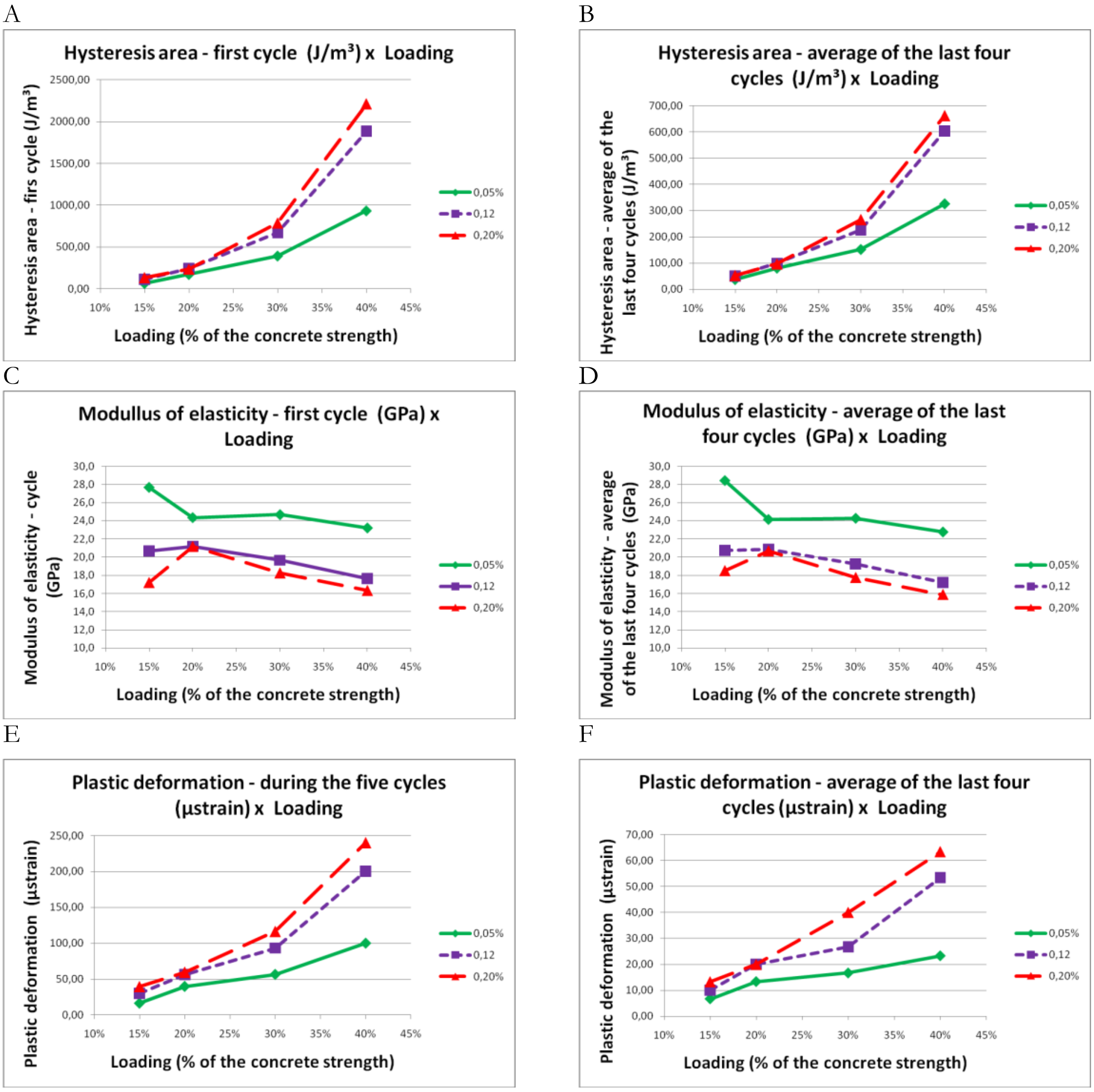
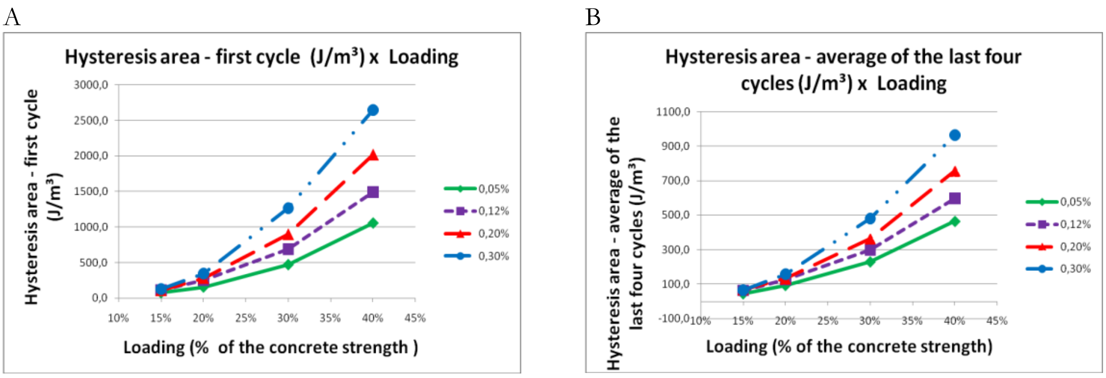


Figure 2. SDT output parameters versus applied loading (% of the concrete strength) for a 25 MPa mixture with a reactive New Mexico gravel. A,B Hysteresis area. C,D Modulus of elasticity. E,F Plastic deformation.



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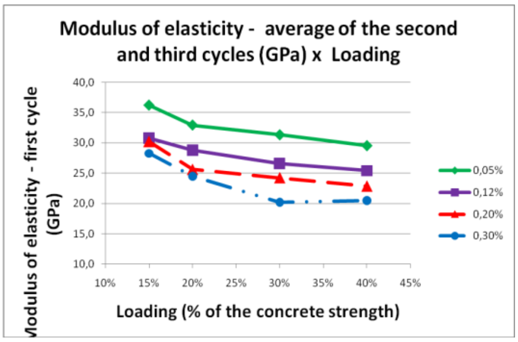

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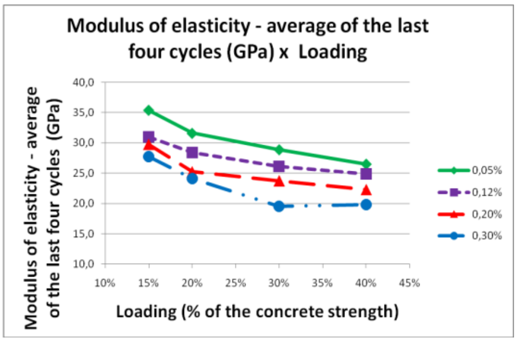

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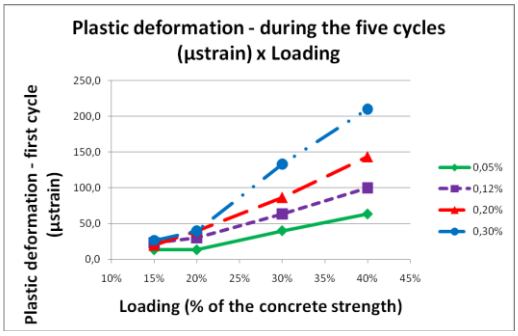

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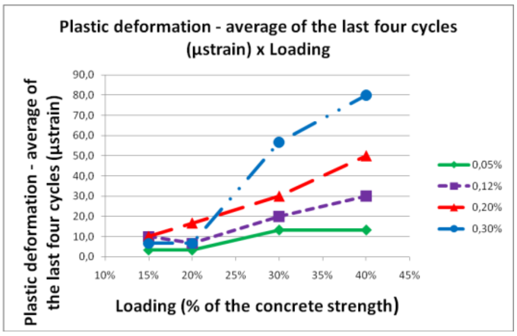
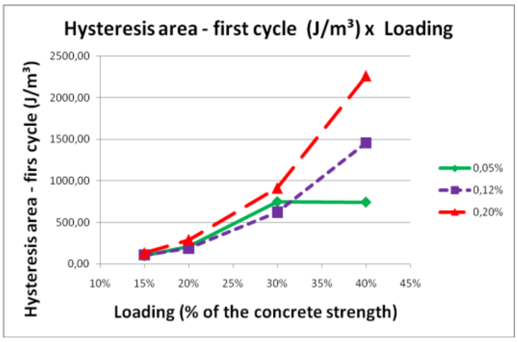


Figure 3. SDT output parameters versus applied loading (% of the concrete strength) for a 35 MPa mixture with a reactive sand (Texas sand). A, B Hysteresis area. C, D Modulus of elasticity. E, F Plastic deformation.

A



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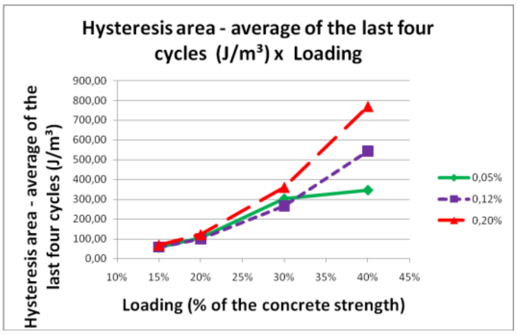

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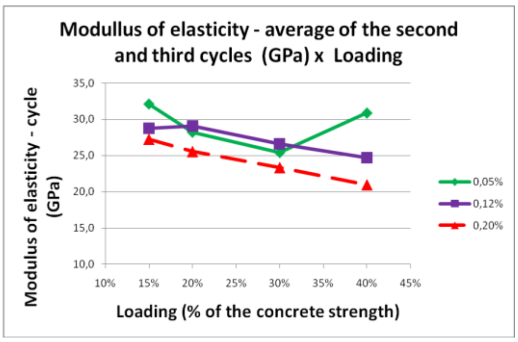

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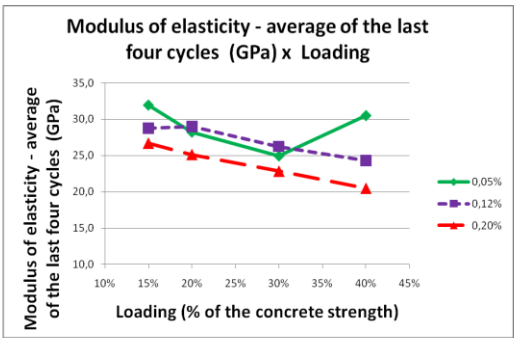

E F

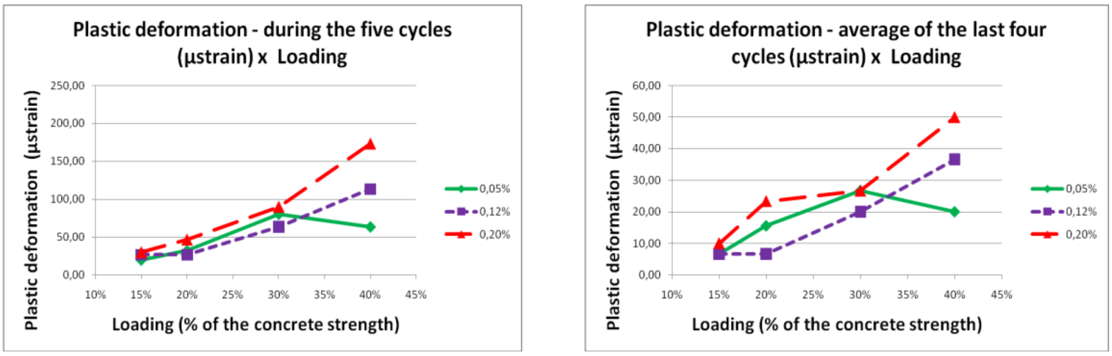

Figure 4. SDT output parameters versus applied loading (% of the concrete strength) for a 35 MPa mixture with a reactive New Mexico gravel. A, B Hysteresis area. C,D Modulus of elasticity. E,F Plastic deformation.

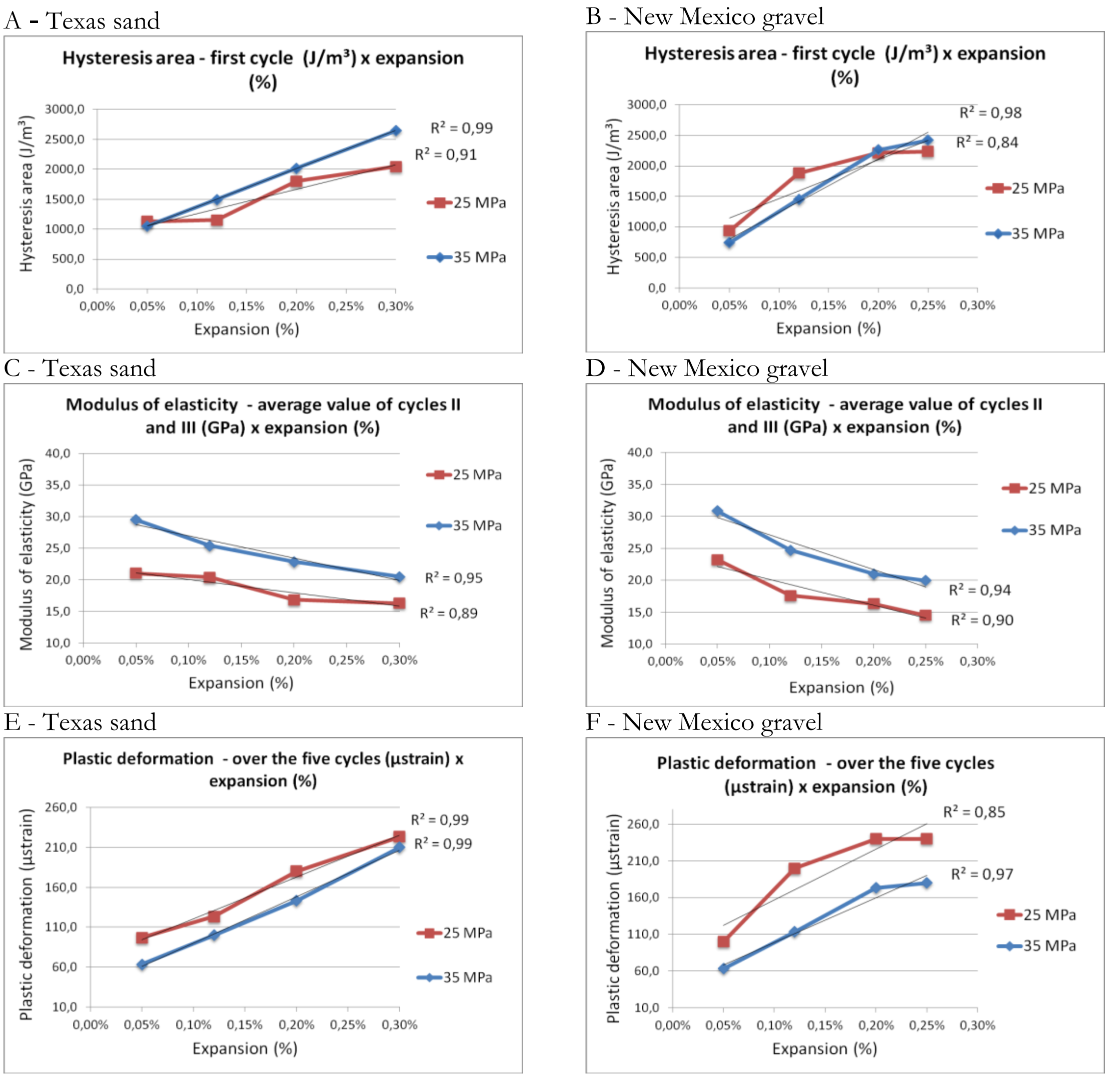

Figure 5. SDT output parameters when 40% of the mix-design strength is used over the test: A, B Hysteresis area. C, D Modulus of elasticity. E, F Plastic deformation.