Correlation of mechanical fatigue testing and semi-quantitative optical microscopy analysis for the robust diagnosis of field ASR damaged structures

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Abstract

The correlation between SDT (Stiffness damage test) and microscopical semi-quantitative analysis of ASR damaged concretes was studied. Bérubé et al. (2005) have proposed a global evaluation tool of ASR damaged structures, by using the correlation between SDT and DRI (damage rating index). This promising approach is here further investigated with several Swiss Alps and Central African concretes. DRI was replaced by a microscopical thin section semi-quantitative analysis of damages.

SDT consists in measuring the axial deformation of cores (d = 100mm) under cyclic compression loading. The test consists of 5 complete load and unload cycles. The static elastic modulus, the cumulative residual plastic deformation at the end of the 5th cycle and the dissipated energy are determined. The dissipated energy corresponds to the energy used to close cracks formed by the damage of concrete induced by ASR.

Good correlation was found between the two techniques. This combined investigation technique consisting of a precise but localized microstructural analysis and mechanical tests on d100 mm cores, proposing a more representative volume, was shown to be a powerful methodology for the good understanding of the state of damage of several parts of a damaged structure. The understanding of ASR damages and progression in the different parts of structures was increased.

Preliminary results encourage undertaking further studies, in order to improve the diagnostic of ASR damaged field structures and enable a robust monitoring over long term.

***Keywords**: ASR; diagnosis; microscopy; optical; SDT*

1. INTRODUCTION

1.1 Influence of ASR on mechanical properties

Compressive strength is in general only affected by ASR as the reaction is already in an advanced state [1]. However, ASR induces a loss of tensile strength and of elastic modulus of concrete already in the earlier states of the reaction, as soon as the crack pattern progresses from the reactive aggregates into the cement paste. This behavior is useful as it allows to get information about the ASR damages before the concrete reaches advanced states of degradation. e.g. [2].

1.2 Assessment of ASR damage development

ASR is the first non-reinforcement-related cause of concrete degradation in the world. The reaction can take up to 30 years to develop in a significant way. One of the main challenges of civil engineering is to establish a correlation between the observed signs of deterioration on concrete structures and their effective loss of mechanical properties.

Several measurement and diagnosis methods were developed over the past decades to get a better understanding of the ASR damage development, as for example:

- *Damage Rating Index (DRI)* e.g. [3, 4, 5]
  DRI consist of a grid counting of cracks and ASR related damages on a binocular microscope (16x). Each default type is multiplied by a ponderation factor. DRI is a powerful method for evaluating ASR damages in a concrete core. It also has the advantage to cover a quiet representative surface of measurement, as ASR is known to be humidity, stress and porosity dependent, its occurrence in a concrete structure can strongly vary depending on where the pathology is observed. The limitation of this method is the resolution of analysis, that only

partially allows to recognize diseases and doesn't get an evidence of the pathology, as for example crystallization products.

- *Stiffness Damage Test (SDT)* e.g. [1, 6]
  SDT consists in measuring the axial deformation of cores (d = 100mm) under cyclic compression loading. The test consists of 5 complete load and unload cycles. The static elastic modulus, the cumulative residual plastic deformation at the end of the 5th cycle and the dissipated energy between the loading and unloading of the 1st cycle are determined. The dissipated energy corresponds to the energy used to close cracks formed e.g. by ASR. This test is a powerful tool for the assessment of ASR on concrete structures, as it is the most representative in term of sample size. The limitations of this test are numerous: the origin of the cracks and damages cannot be directly related to ASR (other pathologies like sulphate attack, freeze-thaw, or static cracks, possibly combined, cannot be excluded in the damage pattern). It is also to mention that the SDT evaluation remains a relatively new investigation method, still lacking experience.
- *Microscopical analysis (on thin section)*
  Optical microscopy on thin section is a powerful tool for microstructural evaluation, and especially for ASR diagnosis (and other pathologies), giving information about the repartition of ASR signs like cracks, ASR reaction product, occurrence of microcracks (<10 microns), but also the morphology and crystallinity of reaction product, giving information about the approximate age of the product. This method also allows to understand the origin of the damages observed. Unfortunately, classical microscopy evaluation methods are qualitative and descriptive, and do not inform about the state of progression of ASR in a given structure. Moreover, the thin section analysis surface is very small (about 2 cm x 4 cm), which is often too small for a representative diagnosis. The preparation of several thin sections is usually necessary to realize a representative investigation.
  Several studies e.g. [7] showed the efficiency of SDT tests on ASR diagnosis of concrete structures. Correlation between SDT dissipated energy and the DRI was showed. It was also proposed that the use of the Stiffness Damage Index (SDI) was an even more accurate value for the diagnosis of ASR damages. SDI is a factor representing the relation between the dissipated energy during the first cycle and the total energy of the first loading.

1.3 Aim of this study

In this work, SDT results were correlated with a new microscopical semi-quantitative analysis method on thin sections.

The combination of the two methods was shown to be a powerful tool to get an accurate long term diagnosis, as both techniques present their own advantages: microscopical analysis on thin section give important information about ASR, as for example number and type of sites of development, reaction product amount and crystallinity, cracks morphology and origin, etc. SDT inform about the intensity of the crack pattern over a more representative volume.

The combination of this two methods is a useful tool for civil engineers, as they can use them for the structural evaluation of ASR affected elements, for the diagnosis of ASR, for the evaluation of the mechanical properties, but also to notice the evolution of the ASR over long term with several investigation campaigns.

This work also aims to validate the semi-quantitative microscopical analysis through the correlation with confirmed mechanical results.

2. MATERIALS AND METHODS

2.1 Materials

Five concretes from structures located in the swiss Alps, and one concrete from a central African dam were investigated.

Table 2.1: Characteristics of the investigated concrete

Name	Location	Structure type	Aggregate type	Age [year]
BE	Swiss Alps	Pylon basement (ski resort)	mainly siliceous limestones, gneisses, quartzite	25
RO	Swiss Alps	Railway bridge		50
SM	Swiss Alps	Highway bridge		40
SR	Swiss Alps	Wastewater treatment plant		40
GD	Swiss Alps	Penstock basement		65
IN	Central Africa	Hydraulic structure (dam)		35 - 45

Cores with 100 mm diameter were extracted from the structures. The cores were taken over the entire depth of elements, in order to get several analysis steps through the deep concrete structures. For each step, the thin section specimens were extracted as close as possible to the mechanical (SDT) testing specimens.

Except for the Central African samples, the mechanical tests were provided within the first 72 hours after drilling to reduce unexpected effects of sample drying [8], especially to avoid a possible drying of ASR reaction products.

2.2 Methods

2.2.1 Microscopical analysis

After drilling, cores are carefully transported to the laboratory. The sample preparation is done as follows: drying at 80°C during 3 days in a ventilated oven, degassing of the core and isotropic impregnation with an epoxy resin at high pressure (300 to 250 bars). The thin sections are obtained by progressive polishing with decreasing diamond powder size, in order to avoid further damages of the microstructure.

The microscopical analysis is made with the use of transmission natural light, transmission polarized light, and reflection UV light. Thin sections are impregnated with fluorescein containing epoxy for the assessment of cracks and faults in UV light.

Over the past years, the TFB team developed a semi-quantitative evaluation method: The detailed microscopic examination on thin section corresponds to the determination of the microstructure parameters of a concrete (assessing its characteristics in a qualitative or semi-quantitative manner as appropriate), increased by a specific description of faults and damages. The following main microstructure parameters are considered (and their distribution inhomogeneity if applicable): degree of hydration of the cement paste, capillarity of the cement paste, macro porosity of the cement paste, interface between the cement paste and the aggregates, the aggregates type and their porosity, cracks, mineralization and recrystallization (e.g. ASR damages), carbonation of the cement paste, as well as various and specific aspects like the type of cement, the presence of mineral additions, the description of faults or damages. The semi-quantitative evaluation of each parameter is done by counting the number of faults over the thin section. It is classified in 5 grades (including half grades) from “none” to “highly frequent” respectively “very high”.

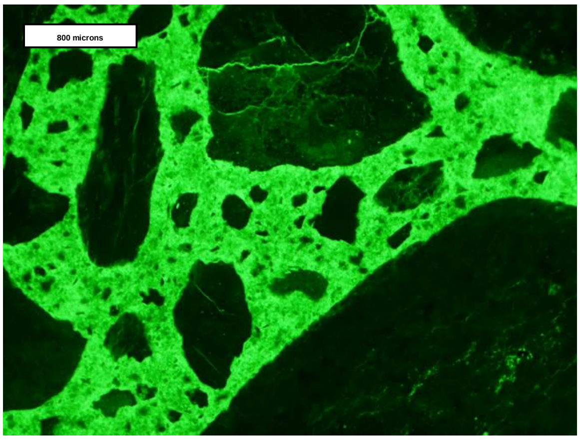
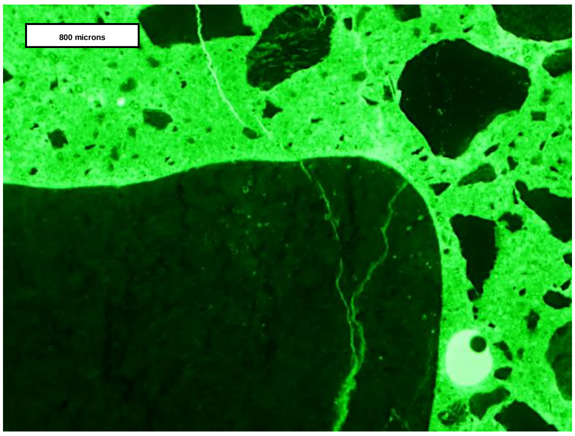
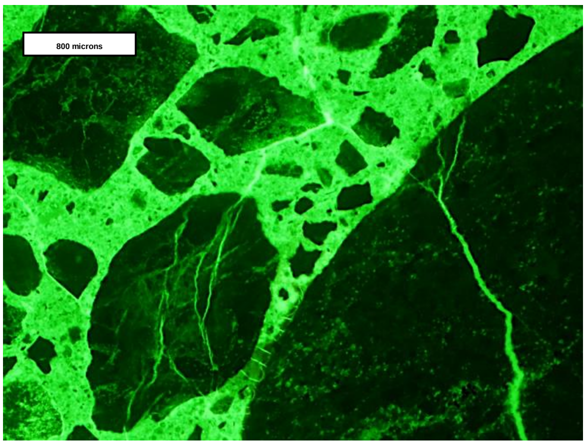
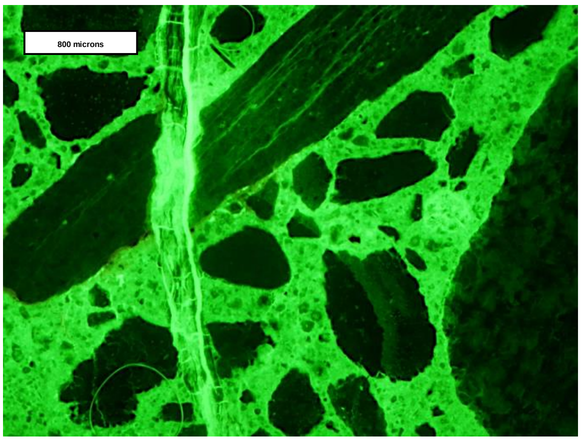
Concerning the ASR occurrence, the counting is separated in five levels following the table 2.2. Three domains were defined as a function of the length and position of the cracks: the initiation domain, corresponding to a “non-pathological” state, were ASR cracks do not cross the aggregates boundaries and showing no decohesion between paste and aggregates; the transition domain, were cracks start to cross aggregates boundaries; and finally, the ASR development domain, that is defined as a “pathological” state, were cracks cross aggregates boundaries in a significant way and/or there are signs of decohesion between paste and aggregates. At this state, ASR affects mechanical and durability properties of concrete.

Finally, an estimation of the intrinsic quality of the material is deduced from these parameters, following a scale of five grades: very good, good, average, poor, very poor.

Table 2.2: Microscopical evaluation, the ASR occurrence levels

	ASR microscopical occurrence	ASR domain
ASR development level	none, rare	initiation: non pathological
	rare/± frequent	
	± frequent	transition: begin of pathological
	frequent	development: pathological
	highly frequent	

Example of micrography for four typical ASR occurrences (the entire thin section analysis is needed for the evaluation):

none, rare:	± frequent:
	
frequent:	highly frequent:
	

The method was validated by comparative analyses over a period of 20 years and 4 operators. The method shows a great accuracy and a very low percentage of subjective interpretation between operators.

2.2.2 Mechanical tests

SDT consists in measuring the axial deformation of cores (d = 100mm) under cyclic compression loading. The test consists of 5 complete load and unload cycles. The applied maximum strain for the cycles is 10 MPa. The loading strain rate is 0.1 MPa/s. The unloading is done at the same rate.

From this test, the following data’s can be obtained: Dissipated energy during the first cycle, residual deformation after 5 cycles, elastic modulus after first and fifth cycle.

Finally, compressive strength was determined following the test standard SN EN 12390-3. The test was done on the same specimens as for SDT.

3. RESULTS

The Figure 3.1 presents the correlation between the elastic modulus and the ASR microscopical semi-quantitative occurrence. As already known [1,2], the increase of the ASR occurrence results in a decrease of the elastic modulus. Despite the quite high dispersion of the correlation, it confirms the effect of ASR on the reduction of elastic modulus. It also correlates and validates the microscopical semi-quantification method with a mechanical measurement.

It is possible to estimate the original elastic modulus of an undamaged concrete, using equation 7-1 of the Fib CEB-FIP (bulletin 70), Code-type models for concrete behaviour (by using the effective compressive strength and admitting that ASR didn’t affect it yet). The ASR most affected concrete of this study presented a decrease of the actual elastic modulus compared to the calculated one. This correlation can be seen in the Figure 3.2.

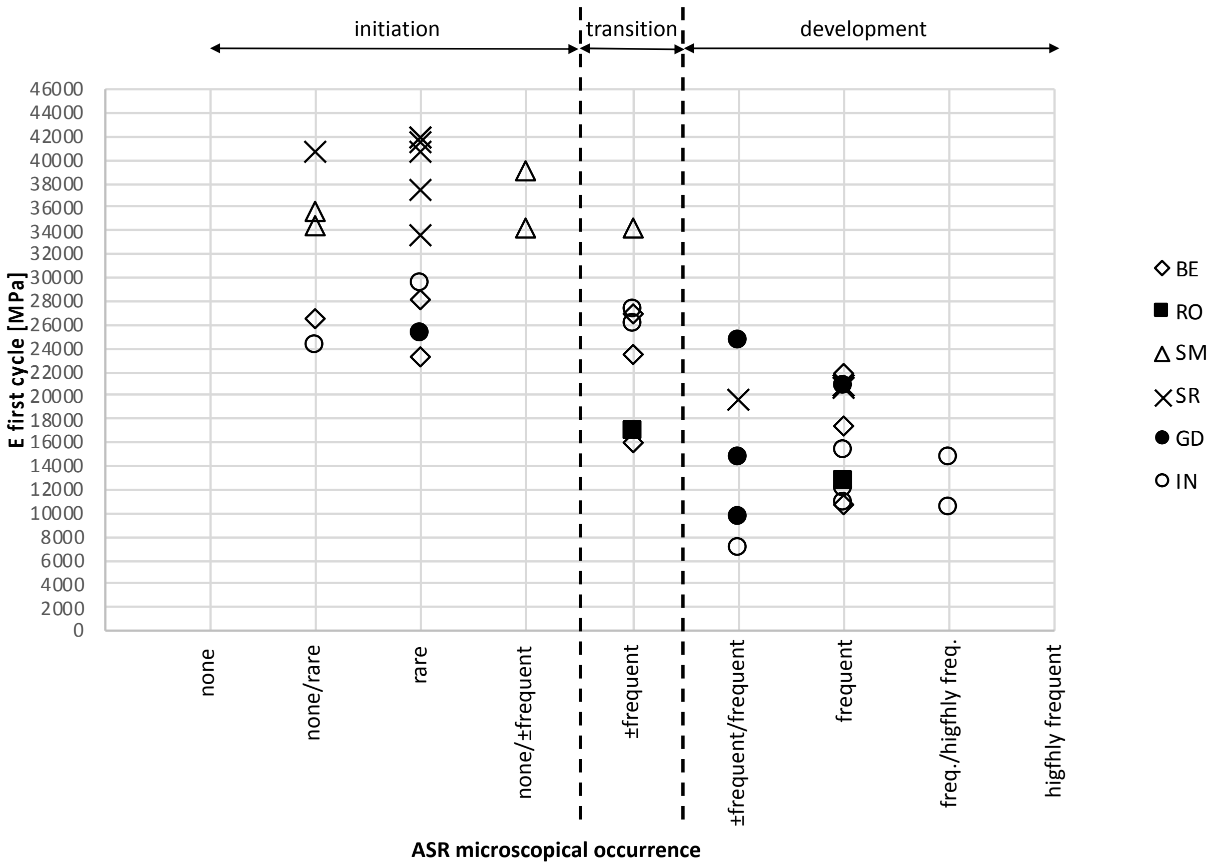


Figure 3.1: Elastic modulus compared to the microscopical ASR occurrence

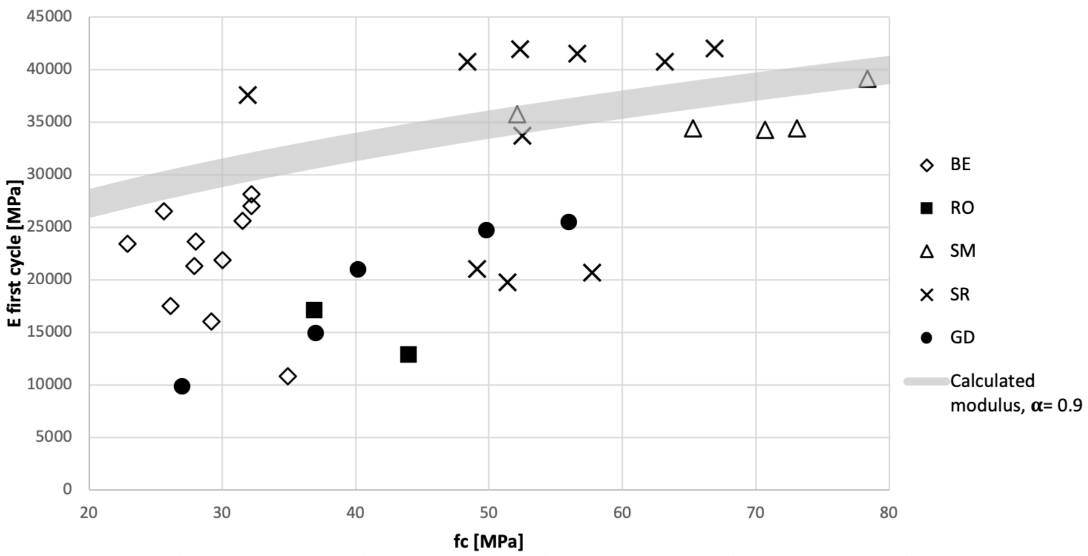


Figure 3.2: Elastic modulus compared to the compressive strength (grey curve: calculated modulus for undamaged concrete)

The Figure 3.3 compares the dissipated energies of the five studied concretes with the microscopical semi-quantitative ASR occurrence. There is a good correlation between the microscopical observed degree of damage in a field concrete, and the dissipated energy obtained by SDT.

When the ASR microscopical semi-quantitative occurrence classifies the concrete in the initiation domain (non-pathological state), the dissipated energy stays below 500 J/m³. When the ASR microscopical semi-quantitative occurrence classifies the concrete in the transition domain, the dissipated energy is between 200 to 1200 J/m³. When the ASR microscopical semi-quantitative occurrence classifies the concrete in the development domain (pathological state), the dissipated energy is always higher than 500 J/m³. Also, the higher the observed ASR occurrence, the higher the range of dissipated energy.

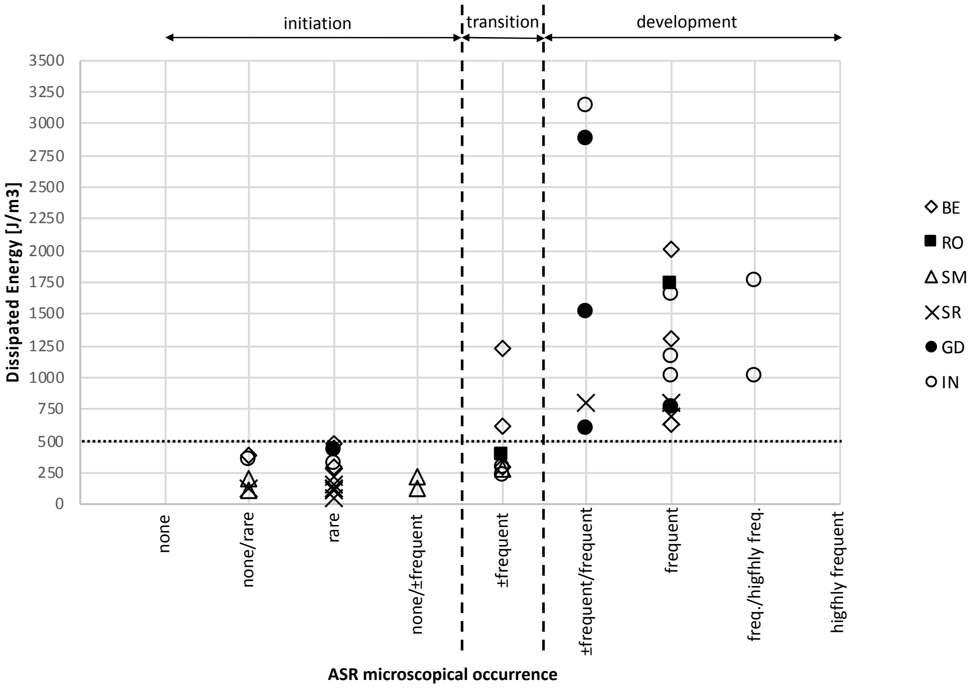


Figure 3.3: Dissipated energy after the first load cycle of SDT compared to the microscopical ASR occurrence

The Figure 3.4 presents the good correlation between the energy dissipated during the first cycle of SDT, and the residual deformation after the fifth cycle.

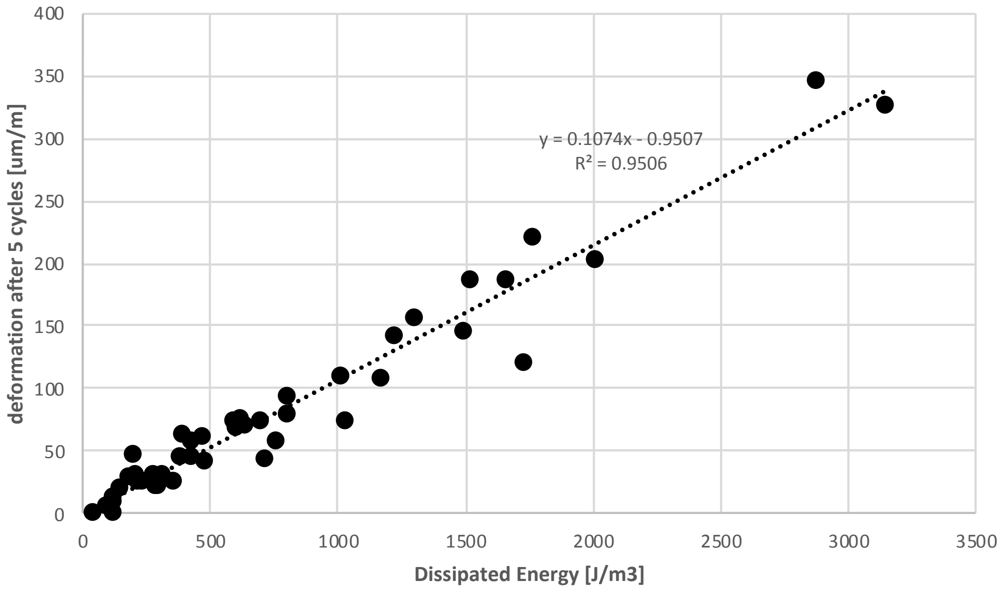


Figure 3.4: SDT: Plastic deformation compared to the energy dissipated during the first load cycle

The Figure 3.5 presents the correlation of the Stiffness damage index (SDI)

SDI = SI / (SI+SII)

with

SI = dissipated energy during the first cycle

(SI+SII) = total energy of the first loading

The Figure 3.6 presents the relation between the SDI and the dissipated energy. At higher dissipated energies, the correlation tends to flatten.

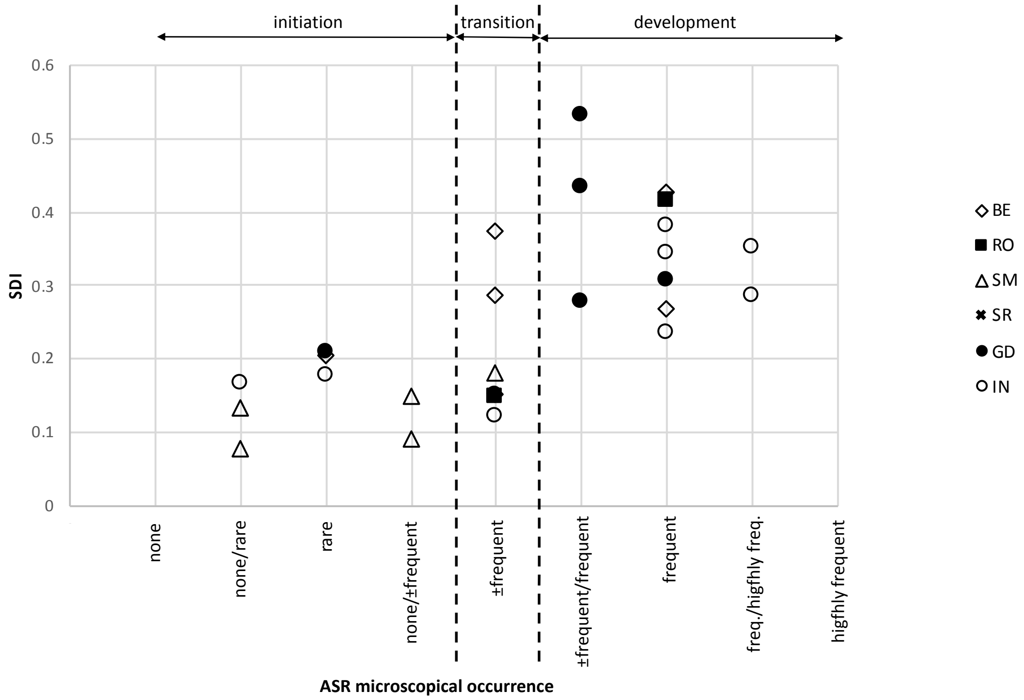


Figure 3.5: Stiffness Damage Index (SDI) compared to the microscopical ASR occurrence

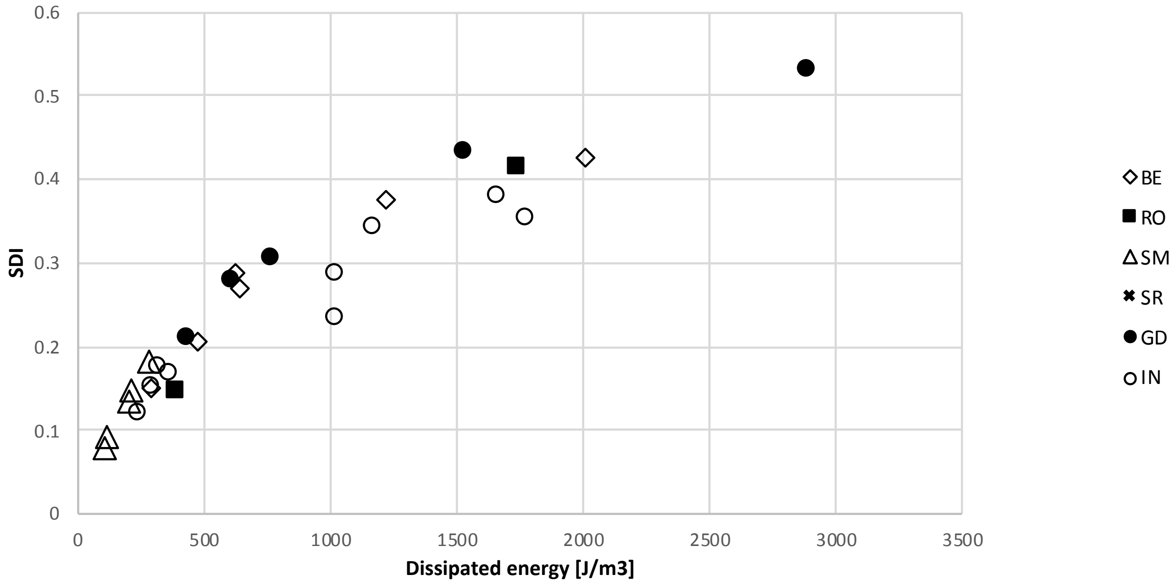


Figure 3.6: SDT: SDI compared the dissipated energy after the first load cycle

4. DISCUSSION

In the graphic of the Figure 3.3, no difference was observed between all the studied concretes as to the correlation between dissipated energy and microscopical semi-quantitative ASR occurrence. The correlation is independent of the concrete type, structure type, age, or aggregate type. This observation confirms that the parameters considered for the microscopical assessment of ASR are mainly related to the crack pattern, which is the only parameter that influences the amount of dissipated energy. Coupled with the fact that the correlation between mechanical properties and microstructural quantification is rather good, these are indicators for the objectivity (non-subjectivity) of the microscopical observation method. This study is a robust way to validate, through the comparison with mechanical results, the developed optical microscopy semi-quantitative ASR occurrence method.

It was observed that when the microscopical semi-quantitative ASR occurrence reaches the transition and development domains, the range of possible dissipated energy gets bigger than in the initiation domain. This widening of the result field in the more affected concretes is mainly due to the fact that field concrete that undergoes ASR can be affected in various ways in terms of cracking. The cracks pattern depends on several parameters as for example the type of aggregates, the exposition to humidity, the freeze-thaw cycles that can increase crack pattern near the surface, the kinetic of ASR, the calcification of ASR reaction products that can lead to their hardening, the confinement of the concrete in the structure (for example due to the effect of reinforcement, due to the concrete mass, etc.) that can reduce or orient cracking, etc. The thin section analysis can detect certain of these influence parameters, however, as the surface of analysis is very small (2 cm x 4 cm), it is possible to miss some of them.

In order to get the full picture of the cracking pattern, and to understand the obtained mechanical results, it is of first importance to cross the SDT results with other information, such as the detailed microscopical observation, the position and orientation of the tested cores in the structure and the detailed visual inspection of the structure, including its environmental exposition.

For example, on the chart of Figure 3.3, samples having a dissipated energy higher than 1400 J/m^3 at an ASR occurrence of “±frequent/frequent” are samples that have been subject to particular influences on their cracking: certain of these samples were extracted near the surface of concrete elements undergoing freeze-thaw cycles and show visual evidence of wide opened cracks at the surface (GD), others were extracted at the surface of mass concrete without any rebar reinforcement, showing important cracking at the surface of the structure (IN). These particular conditions can explain the higher dissipated energies.

For the ASR occurrence classified as “frequent”, three samples present relatively low dissipated energy (between 600 and 750 J/m^3). Again, the crossing of information enables to understand these results:

two of these samples present consequent amount of recrystallized (calcified) reaction product in cracks, involving a clogging of the cracks (SR, BE), whereas the third one was taken in a confined zone at a depth of 300 cm from the surface, involving potentially oriented cracks or narrow cracking pattern (GD). These particular conditions can explain lower dissipated energy.

For the ASR occurrence classified as "±frequent", two samples present relatively high dissipated energies (>500 J/m^3) (BE), and three samples relatively low dissipated energies (< 500 J/m^3) (BE, RO, IN). In this so-called transition domain, samples must be compared to other samples of the same structure, to the visual inspection of the structure, and to all the parameters described above, in order to attribute them either to the initiation or to the development domain.

The Stiffness damage index (SDI) proposed by [7], that also gives a good correlation with the microscopical semi-quantitative ASR occurrence analysis, was not further used for the assessment of ASR affected structures in this study. It appears that SDI has the tendency to lower the range of results in the development domain compared to the raw dissipated energy (cf. charts in Figures 3.5 and 3.6). This is not desired in our case: as the microscopical semi-quantitative ASR occurrence analysis only has 5 grades of quantification, the higher range of the dissipated energy is a precious additional indicator of the potential damage in the structure.

5. CONCLUSION

The microscopical semi-quantitative ASR occurrence method could be well correlated with the mechanical SDT, especially by using the dissipated energy after the first load cycle. The obtained results show that the SDT dissipated energies are of great importance to refine the microscopical observations. The combination of both methods coupled with the detailed visual inspection of structures is a powerful method for the robust diagnosis and long-term investigation of ASR affected structures. The crack pattern could be better understood and characterized, especially in cases where ASR is already diagnosticated as pathological (most critical state).

The use of a mechanical test was also of great importance to validate the semi-quantitative microscopical analysis method developed by the TFB for the assessment of ASR. Microscopical analyses are often operator depending observations with a high part of subjectivity. The developed procedure was shown to be a robust analysis method, showing low subjectivity in the assessment of concrete microstructural parameters, especially for ASR diagnosis.

Further investigation has to be done in order to increase the database and to strengthen the observed correlations. Some refinement of the microscopical semi-quantitative analysis may also able to improve the correlation between SDT and microscopy: correction factors could be included to the ASR occurrence quantification in presence of perturbating parameters, like for example, confinement, reaction product crystallization, etc.

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