SEMI-QUANTITATIVE CONDITION ASSESSMENT OF CONCRETE DISTRESS THROUGH THE DAMAGE RATING INDEX

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Abstract

The Damage Rating Index (DRI), a microscopic and semi-quantitative petrographic tool, is a method which has increasingly been used in North America and Europe, since it may answer some interesting questions about the nature and current condition of damaged concrete. However DRI has mostly been performed on ASR-affected samples and there is currently very few data on the evaluation of other distress mechanisms, such as delayed ettringite formation (DEF), freezing and thawing cycles (FT), etc. This work presents the microscopic assessment of 35 MPa concrete mixtures affected by ASR, DEF and FT, with the aim of verifying the comprehensive diagnostic character of the DRI for assessing distress in concrete. The results show that the DRI number enables the global evaluation of concrete distress, disregarding the damage mechanism type. Moreover, the use of an extended DRI makes still easier the understanding of the development of different distress processes against the expansion levels of affected specimens.

Keywords: alkali-aggregate reaction, crack detection, degradation, damage rating index, durability

1 PETROGRAPHIC COMMON FEATURES FROM DIFFERENT DAMAGE MECHANISMS IN CONCRETE

1.1 Introduction

Several distress mechanisms can affect the long-term durability of concrete, whose "patterns" were diagrammed by St-John et al. and BCA [1, 2]. The development of those "patterns" is linked to the type of deleterious mechanism involved and, in fact, is governed by fracture mechanics. According to [3], the cracks' propagation occurs when the energy released over their propagation is larger than the fracture energy needed to propagate the cracks. The paths chosen by the crack's propagation must follow the principle of minimum energy, i.e. where the elastic energy is released with the minimal use of the fracture energy. Thus, cracks will always choose "preferential paths" for propagating (i.e. either the smallest path in the case of a cement paste or the interface paste/aggregate – ITZ, in the case of a mortars or concretes). Sometimes, cracks can take shortcuts if the path through the aggregate particles is shorter than going through the ITZ [3]. Several researchers have studied the distress features provided by different damage mechanisms in concrete and even though this issue is still not totally understood, the main remarks are the following [3]:

1.1.1 *Shrinkage of the cement paste*

The shrinkage of the cement paste creates radial and tangential stresses in both the cement paste and the aggregate particles. However, the stress often found in the latter is a hydrostatic compression while the stress found in the cement paste is either radial compression or tangential tension. According to [3], cracks develop when the tangential stresses exceed the tensile strength of the material. In addition to existing tensile stresses, shear stress leads to the formation of shear cracks at the boundary between the aggregate particles and the cement paste, although the compressive stresses in the radial direction are transferred across the crack. Usually, when thin section analyses are performed on concrete specimens subjected to shrinkage, it is possible to observe the presence of opened radial cracks combined to very thin (or less opened) tangential (shear) cracks throughout the ITZ (Figure 1a).

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1.1.2 Swelling of the aggregates: the alkali-aggregate reaction (AAR)

In the cases of AAR (mainly for alkali-silica reaction - ASR), cracks are generated at the reactive zones (i.e. where reactive forms of silica are present) within the fine and/or coarse aggregate particles and normally they propagate through the above particles, the ITZ and/or the bulk cement paste, associated with secondary reaction products (e.g. alkali-silica gel) [3,4].

According to [5], different reactive aggregate types exhibit different kinetic behaviours which change depending on their mineralogical composition. Therefore, the distress generated by ASR is highly dependent on the type (fine vs. coarse) and nature (lithology) of the reactive aggregate used. The main differences found by [5] were the expansion kinetics and amplitude, the periods of distress initiation, the sites and sizes of the cracks, the presence of gel in the cracks/pores as well as the development of reaction rims at the periphery of the reactive aggregate particles.

According to [3], the distress caused by ASR provides tensile stresses within the aggregate particles as well as compressive stresses in the external parts of those particles. Thus, cracks are generated inside the particles and, as the expansion level increases, the cracks run out to the cement paste. Since the cracks development rate is always faster than the rate of the stress propagation, cracks will be generated inside the aggregate particles (in the tensile zones) and then run out radially through the cement past [3]. In most cases, the ITZ remains intact, except in the zones near the radial cracks formed inside the aggregates particles [3]. Figure 1b illustrates the typical distress pattern found for ASR cases.

1.1.3 Chemical/physical phenomena in the cement paste: the delayed ettringite formation (DEF) and freezing and thawing (FT)

Chemical/physical phenomena happening in the hardened cement paste can lead to the expansion of the cement paste itself. The stresses generated upon swelling of the cement paste are exactly the same than those produced by the shrinkage effect, but with the opposite signal [3]. The swelling of the cement paste provides hydraulic tensions inside the aggregate particles as well as radial (in tension) and tangential (in compression) stresses in the cement paste. The radial tension peaks at the ITZ; therefore; cracks will develop in this zone, having the characteristics presented in Figure 1c [3]. If the tensile strength of the aggregate particle is lower than the tensile strength of the ITZ, the fracture zone will occur inside the aggregate, at a zone outlining the particle (i.e. parallel to the ITZ). The sketch presented in Figure 1c might also be applied for aggregates subjected to shrinkage.

2 THE DAMAGE RATING INDEX: A TOOL FOR CONCRETE CONDITION ASSESSMENT

Grattan-Bellew and co-workers [6-8] proposed the Damage Rating Index method (DRI), which consists in a semi-quantitative analysis of distress petrographic features on polished concrete sections. The DRI is performed with the use of a stereomicroscope (15-16x magnification) where damage features associated with ASR are counted through a 1 cm^2 grid drawn on the surface of a polished concrete section [9]. The number of counts corresponding to each type of petrographic feature is then multiplied by weighing factors, whose purpose is to balance their relative importance towards the mechanism of distress (for instance ASR). It is important to mention that the factors used in the method were often chosen on a logical basis, but relatively arbitrarily [9]. Ideally, a surface of at least 200 cm^2 should be used for analysis, and it may be greater in the case of mass concrete incorporating larger size aggregate particles. However, for comparative purposes, the final DRI number is normalized to a 100 cm^2 area [9].

The DRI has increasingly being used [10-14], as well as other petrographic methods [15-20], with the objective of quantifying the condition of concrete affected due to ASR, thus avoiding criticism of being a qualitative and narrative assessment [9, 21]. However, the DRI has not been normalized so far and important deviations were found among different operators carrying out the method. In order to reduce those deviations, [9] proposed to improve the description/definition of the different distress features over the test, to train the operators with the use of standard samples and to eliminate the counting of both the number of voids with reaction products in the cement paste and of the reaction rims. Also, weighing factors of 2 or 3 were proposed for cracks in the aggregate particles and the cement paste, respectively, with the presence or not of reaction products, thus reducing the variability associated with the difficulty to recognize the presence of reaction products in the cracks at the DRI magnification level. Figure 2 illustrates the weighing factors proposed by [9].

Using the new approach proposed by [9], [4,22] used the DRI to study the condition of 25, 35 and 45 MPa concretes incorporating a variety of reactive fine and coarse aggregates. Parameters such as the DRI number, the crack density and the distress features assessment (both in counts or in %) were found to be powerful output parameters that could be used for the condition assessment in AAR-affected concretes.

Bérubé et al. [23] used the DRI method for assessing damage in concretes affected by freezing and thawing (FT) and DEF. The results showed that the DRI was influenced by the water-to-cement ratio of the concrete (lower DRI with a higher w/c ratio) as well as by the presence of the entrained air (greater DRI for entrained air concrete). At similar expansion levels, concrete affected by ASR presented much higher DRI numbers than concretes affected by FT or DEF. However, the authors suggested that further work was required for the DRI procedure to become a reliable tool for the assessment of concrete damage.

According to [24-29], a detailed petrographic analysis of concrete cores extracted from affected concrete structures, either on fractured surfaces or thin/polished sections, can help identifying the presence (or absence) of the main microscopic features resulting from various deleterious mechanisms within the distressed material.

Since the process of damage generation vary through either the type of deleterious mechanism involved or the concrete components (i.e. aggregate nature, types, etc.), the DRI should ideally assess the nature and degree of distress within a concrete specimen and correlate it with either the expansion attained or the losses in mechanical properties [9, 10, 11]. Such information is, however very limited. Moreover, although the differences between highly and mildly distressed concrete specimens are generally clear under the microscope [30, 31], there is currently no classification established to separate low, moderate or high damage levels in the DRI. Finally, it is important to mention that even if the DRI has already been used by several researchers, the method has not a standard procedure yet.

3 SCOPE AND OBJECTIVES OF WORK

This paper discusses the use of the DRI for the condition assessment of concretes affected by three different deleterious mechanisms, i.e. ASR, DEF and FT. Among others, this evaluation aims at:

- Understanding the distress development of these three different damage mechanisms in concrete;
- Assessing the different microscopic distress features provided by the different mechanisms as a function of the distress development;
- Evaluating the use of the DRI number as a global tool for evaluating different damage mechanisms in concrete.

4 MATERIALS AND METHODS

4.1 Materials and mixture proportions

All the analyses were carried out on 35 MPa concretes incorporating two extremely-reactive aggregates (New Mexico gravel and Texas sand). The main reactive material in the Tx sand is chert present in the coarser fractions of the aggregate material (~1.25 – 5 mm fractions), while it is chert and volcanic rock (rhyolite/andesite) particles in the case of the New Mexico gravel [4,23]. The reactive sand (Tx) and gravel (NM) were used in combination with non-reactive coarse and fine aggregates, respectively. Table 1 gives the main characteristics of the aggregates selected.

Two types of non-air-entrained concrete mixtures were designed for this work. For ASR, FT and combined ASR+FT studies, 35 MPa concrete mixtures (containing the same amount of paste and aggregates in volume - i.e. from one mix to another), were designed. A CPT mixture (concrete prism test, according to ASTM C 1293 mix characteristics) was used for comparative ASR, DEF and combined ASR + DEF studies.

All concrete mixtures were made with the same conventional (CSA Type GU, ASTM type I) high-alkali (0.90% Na_2Oeq) Portland cement. The total alkali content of all mixtures was raised to 1.25% Na_2Oeq, by cement mass, for accelerating ASR development (Table 2).

4.2 Fabrication and curing of test specimens

4.2.1 *ASR specimens*

A total of 96 cylinders, 100 by 200 mm in size, were cast from each of the four concrete mixtures manufactured in the laboratory (Tx + HP, NM + Lav – 35 MPa mixture and CPT mixture). After casting, the specimens were cured for 48h in the moist curing room. After stripping, small holes, 5 mm in diameter by 15 mm long, were then drilled in both ends of each test cylinders and stainless steel gauge studs were glued in place, with a fast-setting cement slurry, for longitudinal expansion measurements. The cylinders were left to harden for 48 h prior to performing the "0" length reading, after what they were placed in sealed plastic (22 liters) buckets lined with damp cloth (4 cylinders per bucket). All buckets were then stored at 38°C and 100% R.H. and the test cylinders monitored for length changes regularly until they reached the expansion levels chosen for this research, i.e. 0.05%, 0.12%, 0.20% and 0.30%.

As per ASTM C 1293, the buckets were cooled at 23 °C for 16 ± 4 h prior to periodic axial expansion measurements. When the above expansion levels were reached, the specimens were wrapped in plastic films and stored at 12°C until testing (because of testing capacity issues). In order to perform the DRI procedure, the concrete cylinders were first cut in two (axially) and then polished. A portable hand-polishing device, which uses diamond-impregnated rubber disks, was found most suitable as it does not use loose abrasive powders that can fill up cracks/voids in the concrete and quality polishing is obtained with minimal water supply.

4.2.2 Freezing and thawing (FT) and FT + ASR specimens

In the case of freezing and thawing analyses (FT), 48 concrete samples were cast with the same concrete mix-design used for ASR testing (Tx + HP and NM + Lav – 35 MPa mix). After casting, the specimens followed the same procedure as described above for ASR. The specimens were then placed in a cabinet and subjected to eight freezing and thawing cycles per day (3h cycles, from -20°C up to + 5°C). After the first 2 cycles, the "0" reading was performed according to ASTM C 666. Then, the samples were measured axially each day until they reached the same expansions used for ASR studies, i.e. 0.05%, 0.12%, 0.20% and 0.30%. Finally, the samples were cut and polished in order to perform the DRI.

For FT + ASR coupling, 48 concrete cylinders were cast from the same concrete mix-design used for ASR and FT testing (Tx + HP and NM + Lav – 35 MPa mixes). The specimens followed the same procedure performed for the ASR specimens; however, when the samples reached half of the total expansion levels chosen for this research (i.e. 0.025%, 0.06%, 0.10% and 0.15%), they were wrapped in plastic films and subjected to FT cycles until the specimens reached the total amount of expansion used in this work (0.05%, 0.12%, 0.20% and 0.30%).

4.2.3 Delayed ettringite formation (DEF) and DEF + ASR specimens

In the case of DEF analyses, 48 concrete samples were cast at the University of Texas (U.T, Austin, USA) with the CPT concrete mix-design (Tx + MM and NM + ER – CPT mixture, Table 2). Four hours after casting, the specimens were placed in an oven and the temperature raised to 95°C over a 4h period. Then, the cylinders were left for 12 hours at the same temperature. Afterwards, the temperature was lowered down to 23°C within 12 hours. Finally, the samples were immersed in water at 23°C and measured regularly until they reached selected expansions levels, (i.e. 0.12%, 0.40%, 0.50%, 0.80%, ≈ 1.0% and ≈ 2.0%. Once the above expansions were reached, the samples were prepared for the DRI analyses.

For DEF + ASR coupling, 48 concrete samples were cast also at UT with the CPT concrete mix-design (Tx + MM and NM + ER). The procedure performed to develop DEF was also adopted, but instead of soaking the concrete specimens in water at 23°C, they were subjected to conditions conducive to the development of ASR as per ASTM C 1293, i.e. 38°C and 100% R.H. The expansions were then measured over time and the following expansion levels were chosen for analyses: 0.08%, 0.12%, 0.30%, 0.50%, 0.60%, 0.90% and 1.5%.

4.3 Methods for assessment and analysis

The Damage Rating Index was performed, as described in Section 2, on specimens cast from all concrete mixtures at each of the expansion levels selected, according to the procedure proposed by Villeneuve & Fournier [9]. The damage features were counted in aggregate particles down to 1 mm in size, instead of 2 mm such as proposed by [4,23]. The semi-quantitative DRI numbers presented hereafter are the normalized values to 100 cm^2 obtained for a concrete polished section at a given expansion level.

5 RESULTS

Figure 3a and 3b give the plots of the DRI numbers for the affected concrete mixtures cast with Tx and NM, respectively. Figure 4a and b illustrate the different DRI microscopic features for the same mixtures (Tx and NM aggregates, respectively), and for all the distress mechanisms studied in this work. Globally, the DRI numbers were found to increase with increasing expansion in the test specimens, thus allowing distinguishing the different expansion levels/damage degrees chosen for this work. Moreover, for the vast majority of the samples tested, the DRI values correlated quite well (almost linearly) with the expansion levels measured on the concrete specimens. However, the different distress mechanisms sometimes presented different DRI numbers for similar expansion levels. This is related to the location and extent of cracking within the test specimens affected by those different mechanisms (i.e. cracking in the aggregate particles vs in the cement paste), which is then further enhanced by the weighing factors used in the DRI method as proposed by [9]).

Considering the ASR mechanism, the DRI numbers were quite close for the two reactive aggregates over all the expansion levels. For Tx mixtures, the CPT specimen presented greater DRI values than the 35 MPa specimen at similar low to moderate expansion levels (i.e. 0.05 – 0.12%); however, the results were almost the same for higher expansions. In the case of NM mixes, both mixture types showed somewhat similar DRI values at similar expansion levels throughout the interval selected.

Regarding the DEF mixtures, the results of both single and coupled (DEF + ASR) mechanisms were somewhat similar at similar expansion levels; however, when comparing DEF to ASR, one verifies that Tx mixtures presented fairly similar results. On the other hand, this trend was not confirmed for NM mixes, where DEF (and also DEF + ASR) showed a slower rate of increasing DRI as a function of increasing expansion in the test specimens.

Analysing FT and FT+ASR results, one verifies that for the two reactive aggregate types, the DRI results related to FT distress were greater than those obtained for DEF and ASR, at similar expansion levels. Moreover, for NM cases, both FT and FT+ASR results were quite similar, although this trend was not confirmed for Tx mixes, where the coupled mechanism showed a much greater damage throughout the expansion levels.

6 DISCUSSION

The results presented before show that the DRI has the potential for assessing damage in concrete specimens affected by ASR, DEF and FT (single or coupled). Moreover, the detailed analysis of the features of deterioration obtained through the DRI procedure, illustrated in Figures 4a and 4b, showed that the development of damage resulting from the above deleterious mechanisms as a function of the expansion levels was significantly different, as summarized hereafter:

6.1 ASR distress mechanism

In the beginning of ASR (i.e. ≈ 0.05%), cracks are generally generated inside the reactive coarse or fine aggregate particles (OCA and OCAG). CCA often correspond to "pre-existing" cracks generated through natural alteration processes or by the processing operations in aggregate production plants. At this expansion level, there are only limited occurrences of ASR-generated *Cracks in the cement paste* (CCP and CCPG) (at least visible at the DRI magnification). As the expansion increases (i.e. up to 0.12%, for example), the *Opened cracks* formed within the reactive aggregate particles keep increasing (in length and width) and some of them extend into the cement paste. Moreover, up to this expansion level, the presence of alkali-silica gel in the *Opened cracks* (in either the aggregates or the cement paste) seems somewhat limited (at least visible at the DRI magnification).

For higher expansion levels (i.e. up to about 0.20%), most of the *Opened cracks* formed within the aggregate particles reach the cement paste. Likewise, the presence of alkali-silica reaction products can be easily found (mainly within the aggregate particles) at this level. Finally, at a very high expansion level (i.e. 0.30% or greater), the *Cracks in the cement paste* link to each other, thus forming an extensive cracking network. Moreover, fairly similar DRI values were obtained, at similar expansion levels, when ASR is generated from the reactive sand (Tx) or the coarse aggregate (NM), and also between concrete mixes containing different amounts of aggregates and cement paste (i.e. CPT vs 35 MPa mixtures). However, a much finer and somewhat "diffuse" cracking network was found to develop in concretes incorporating the reactive sand compared to when the reaction was generated in the coarse aggregate particles. Also, the presence of gel was easier to notice in mixes incorporating the NM aggregate (i.e. visible at the DRI magnification).

6.2 DEF distress mechanism

Regarding DEF results, a large occurrence of *Cracks in the cement paste* (CCP) is already found for the first expansion level assessed (0.12%); those are mainly present in the interfacial transition zone (ITZ) between the aggregate particles and the cement paste. This clearly separates this mechanism from ASR, despite the presence of some *Opened cracks* within the aggregate particles in the DEF specimens. Actually, some of those cracks, are likely related to ASR that was triggered by the high-temperature treatment and further moisture storage of the test specimens since the aggregates used in this study are highly reactive.

As the expansion level increases (i.e. up to 0.30%), the cracks prior generated increase in length and width, and also some new cracks are formed in the cement paste. Moreover, some cracks are generated inside the aggregate particles, especially for Tx mixtures. For higher expansion levels (≥ 0.30%), an extensive cracking network is observed in the cement paste, which largely increases the crack density within the specimens. Finally, for expansion levels greater than 0.50%, a new phenomenon start appearing: debonding of the aggregate particles, which demonstrates the increase of the overall concrete damage.

6.3 FT distress mechanism

In the beginning of the freezing and thawing cycles and for low expansion levels (i.e. 0.05%), large occurrences of cracks are found in either the ITZ or the bulk cement paste/pores of the cement paste. Moreover, at this expansion stage, some opened cracks are also observed in the aggregate particles (OCA).

As the expansion level increases and for average and high expansion level (i.e. 0.12-0.20%), the cracks already formed keep progressing (in length and width) and some new cracks are also generated both in the cement paste (ITZ or bulk paste/pores)(CCP) and within the aggregate particles (OCA). Otherwise, the development of cracking within the aggregate particles seems to level off. Finally, when the expansion level reaches very high degrees (i.e. ≥ 0.30%) of expansion, the vast majority of the cracks link to each other, resulting in an extensive cracking network formation.

6.4 Combined mechanisms

Although each of the distress mechanisms studied in this research were fully described in the previous sections, some considerations in the mechanisms associations are still needed.

DEF + ASR

The ASR + DEF coupling seems to increase, at similar expansion levels, the amount of Opened cracks in the aggregate particles (OCA) when one compares this coupling to DEF single mechanism (as expected), for all the expansion levels and for both reactive aggregates. Moreover, the development of the crack density does not seem to change as a function of the expansion levels for the coupled mechanism compared to DEF single process. In addition, despite the fact that the coupled mechanism changes the distress features pattern, the semi-quantitative DRI number did not seem to change due to the combined mechanisms as a function of the expansion attained by the affected concrete.

FT + ASR

The ASR + FT coupling seems also to increase, at similar expansion levels, the amount of Opened cracks in the aggregate particles (OCA) when one compares to FT single mechanism, as expected. Moreover, differently from ASR + DEF, the ASR + FT association seems to influence the cracking density of the affected materials, increasing the overall distress over all the expansion levels studied (especially in Tx mixtures). Therefore, it seems the FT mechanism (which took over ASR expansion in this research) takes advantage of some pre-existent cracks within the aggregate particles to develop its "own" damage. However, further analyses are needed in order to provide a better understanding of the mechanisms interactions.

7 CONCLUSIONS

Three different mechanisms (ASR, DEF and FT), acting separately or coupled, were analysed through the Damage Rating Index (DRI) (in qualitative and semi-quantitative basis) as a function of the expansion levels of affected concrete samples. The main conclusions are the following:

- The DRI procedure seems to distinguish/evaluate quite well the three different damage mechanisms (ASR, DEF and FT) studied in this work, especially for the mixtures incorporating the highly reactive NM coarse aggregate;
- Overall, FT and DEF affected concretes presented greater DRI numbers than those undergoing ASR for low and average expansion levels, since those mechanisms generate *Cracks in the cement paste* from the very beginning of the distress process (and the weighing factors for cracks in the cement paste are greater than for cracks within the aggregate particles); thus an in depth study in the weighing factors of the method seem to be the next step for the DRI to become a comprehensive damage assessment tool;
- Compared to the concrete affected by single deleterious mechanisms, combined mechanisms (i.e. ASR + FT and ASR + DEF) either increased or maintained the level of damage (i.e. DRI numbers) within the affected samples for all the expansion levels. Coupled mechanisms were more harmful, mainly for ASR + FT cases and especially when ASR generated finely disseminated cracking network in the cement induced by a reactive sand;

- The DRI appears to have the potential of being an effective tool for assessing (in a semi-quantitative manner) damage in concrete provided by distress mechanisms in concrete.

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TABLE 1: Aggregates used in the study.

Aggregate		Location	Rock Type	Specific gravity	Absorption (%)	AMBT [1] 14d exp,%	Reactivity
Coarse	NM	New Mexico (USA)	Polymictic Gravel (mixed volcanics, quartzite, chert)	2.53	1.6	1.114	R
	HP	Newfoundland (Canada)	High-purity limestone	2.68	0.4	0.001	NR
	MM	North Carolina (USA)	Limestone	2.47	3.1	0.010	NR
Fine	Tx	Corpus Christie (USA)	Polymictic sand (granitic, mixed volcanics, quartzite, chert, quartz)	2.60	0.6	0.995	R
	Lav	Quebec (Canada)	Natural derived from granite	2.71	0.5	0.032	NR
	ER	North Carolina (USA)	Manufactured limestone sand	2.51	4.9	0.070	NR

TABLE 2: Concrete mix-designs used.

Ingredients	DEF and DEF + ASR - CPT		ASR, FT and FT + ASR – 35 MPa		ASR - CPT	
	Texas sand	NM gravel	Texas sand	NM gravel	Texas sand	NM gravel
Cement (kg/m^3)	420 (134)	420 (134)	370 (118)	370 (118)	420 (134)	420 (134)
Sand (kg/m^3)	648 (249)	562 (224)	790 (304)	714 (264)	678 (261)	583 (216)
Coarse aggregate (kg/m^3)	1089 (441)	1148 (454)	1029 (384)	1073 (424)	1093 (408)	1146 (452)
Water (kg/m^3)	176	176	174	174	177	177

[1] The number in brackets correspond to the volume occupied by the materials (in L/m^3).

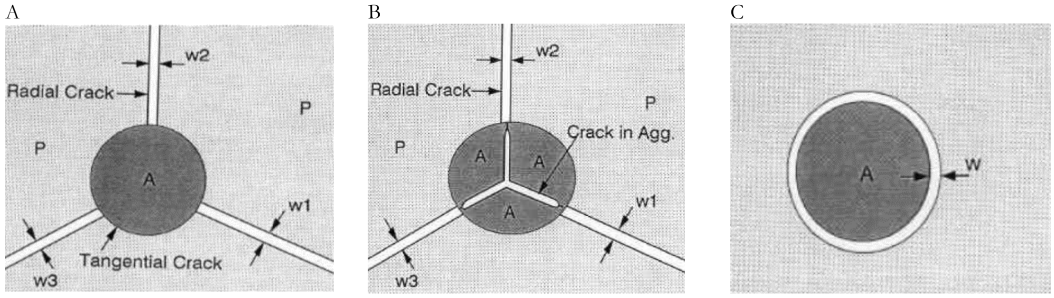


FIGURE 1: signatures of concrete damaged by: A) shrinkage; B) swelling of the aggregates (e.g. asr) and; C) cement paste swelling (or aggregate shrinkage) in concrete (e.g. DEF)[3].

Petrographic features	Abbreviation	Weighing factor
Cracks in coarse aggregate	CCA	0.25
Opened cracks in coarse aggregates	OCA	2
Crack with reaction product in coarse aggregate	OCAG	2
Coarse aggregate debonded	CAD	3
Disaggregate/corroded aggregate particle	DAP	2
Cracks in cement paste	CCP	3
Cracks with reaction product in cement paste	CCPG	3

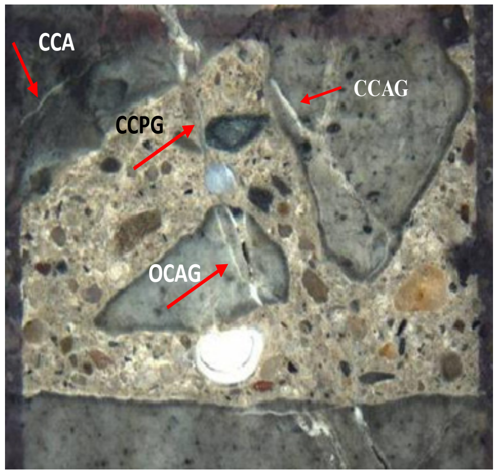


FIGURE 2: Petrographic features to be noted in the Damage Rating Index (DRI) analysis [22].

A – TX mixtures B – NM mixtures

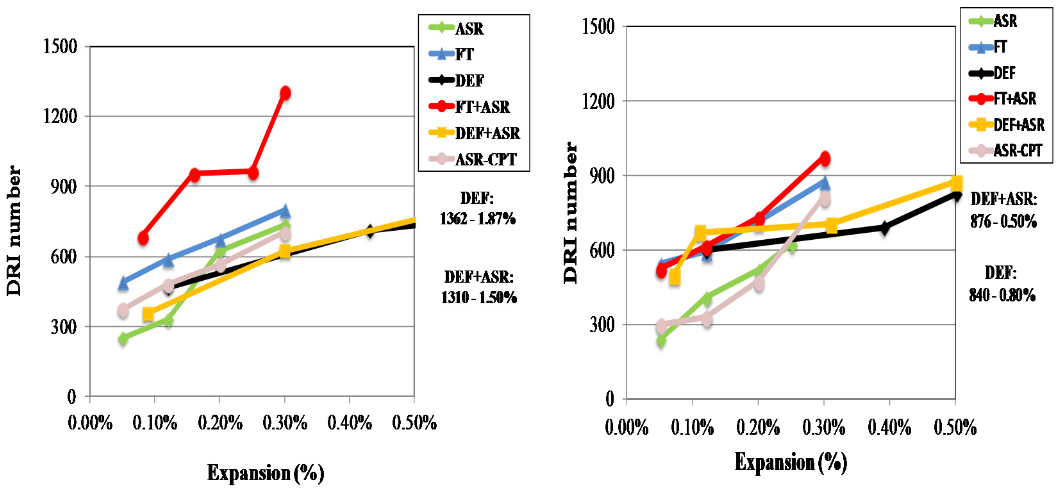
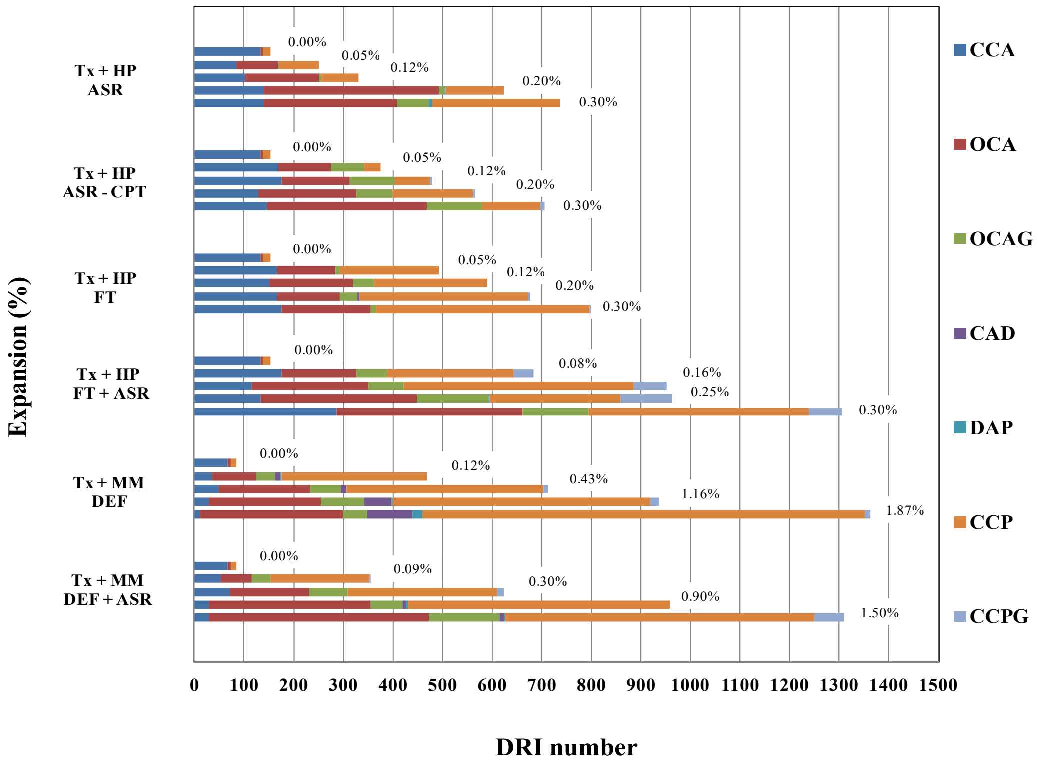


FIGURE 3: DRI values for all the mixtures analyzed over the study: A) Tx mixtures; B) NM mixtures.

A – Tx concrete mixtures



B – NM concrete mixtures

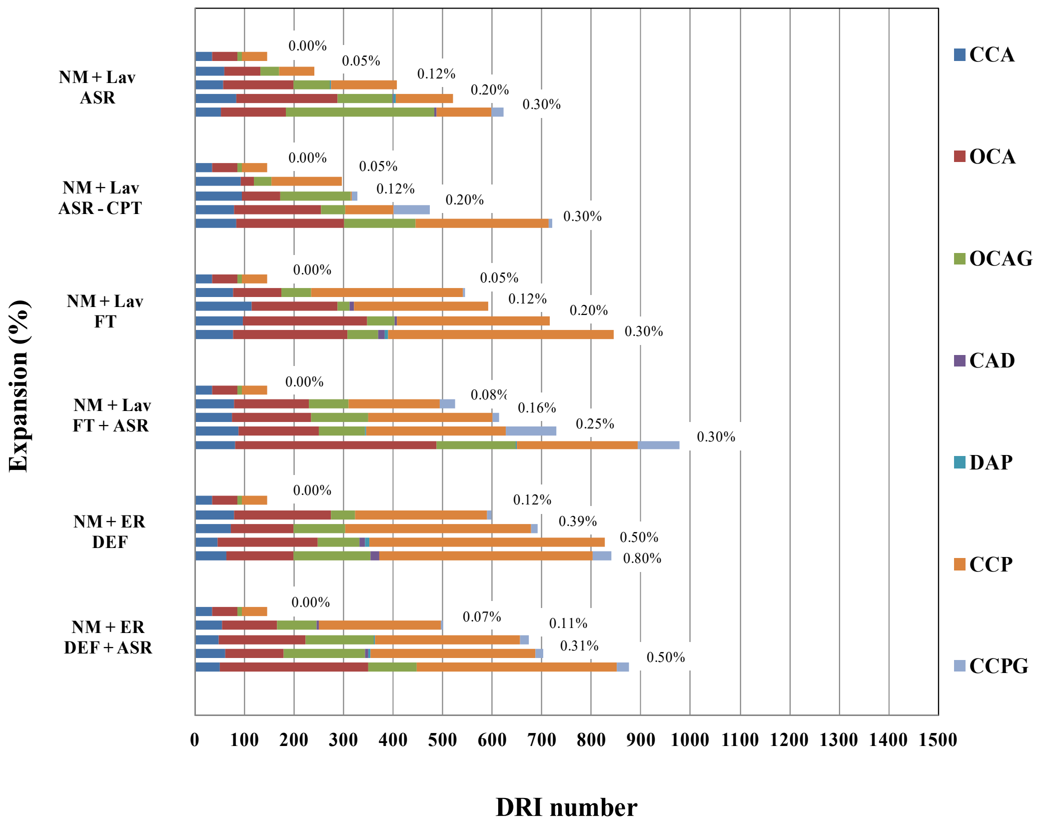


FIGURE 4: DRI charts for all concrete mixtures analyzed: A) Tx mixtures and B) NM mixtures.