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# DETERMINATION OF THE DAMAGE IN CONCRETE AFFECTED BY ASR - THE DAMAGE RATING INDEX (DRI)

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**ABSTRACT** : The DRI consists in a semi-quantitative petrographic evaluation of damage in concrete either affected by ASR or other deleterious mechanisms. The results can however be affected significantly by the experience of the operator. In this study, different approaches were evaluated to identify the various factors responsible for the variability of the test and to propose potential modifications that could improve its reliability. For that purpose, two comparative studies were carried out (involving several operators), while the method was also applied to a number of polished concrete sections obtained from field structures and laboratory specimens showing different degrees of damage and incorporating a variety of reactive rock types.

## 1. INTRODUCTION

Although the development of test methods for evaluating the potential alkali-reactivity of concrete aggregates and selecting effective preventive measures against ASR has progressed to such a point that it is now possible to manufacture concrete risk-free of ASR, the management of existing concrete structures affected by ASR still remains a huge challenge for engineers. Any information on the nature of the deleterious process(es) affecting the structures, their current condition and potential for future deterioration, is generally critical for engineers in charge of selecting appropriate remedial measures. In that context, Grattan-Bellew and coworkers [1-3] proposed the *Damage Rating Index* method *(DRI)*, which consists in the semi-quantitative assessment of petrographic features of deterioration on polished concrete sections. The above method is increasingly being used [4-9], as well as other "parent" petrographic methods [10-16], with the objective of estimating the condition of concrete affected by ASR.

This study has however shown that the DRI results can vary widely according to the experience of the operator. Despite that, the method can provide very useful information when the examination of cores from various parts of a structure (subjected to different exposure conditions or deteriorated at different degrees) is carried out by the same experienced/trained petrographer(s). The method also allows identifying differences in damage ratings between structures that incorporate different types of reactive aggregates, as well as the progress of damage when the test is carried out regularly on deteriorating concrete elements.

## 2. NATURE AND OBJECTIVE OF THE STUDY

Considering the growing interest in the use of the DRI method, a number of petrographers showed interest in developing the method into a standard test procedure. Prior to do so, it appeared appropriate to identify the major source of variation(s) observed between petrographers, so that appropriate modifications could potentially be made to the test procedure.

A two-day *DRI Workshop* was first organized in Canada, in the Fall of 2008. The 20 participants (from North America and Europe) shared their experience in using petrographic methods for ASR-damage assessment, and examined polished concrete sections from ASR-affected structures incorporating different types of reactive aggregates. The current DRI method was critically analysed and an alternative approach was proposed. It was then proposed that comparative evaluations of the two methods would be carried out at Laval University, with the objective of determining the impact of different factors on the variability of the methods. This paper summarizes the results of that study.

## 3. METHODS AND MATERIALS

### 3.1 Description of the *Original DRI method [1-3]*

The *Original DRI method* consists in a count, under the stereomicroscope (≈16x magnification), of the number of petrographic features of deterioration (commonly associated to ASR) on polished concrete sections (Figure 1) on which a grid is first drawn (minimum 200 grid squares to be examined, 1 by 1 cm in size)(Figure 2). The *DRI* thus represents the normalized value (to 100 $cm^2$) of the frequency of these features after the count of their abundance, over the surface examined, has been multiplied by weighing factors representing their relative importance in the overall deterioration process (Table 1 – Original DRI Method).

### 3.2 Development of the *Modified DRI method (1)*

During the DRI determination, the number of cracks present in each aggregate particle and in the cement paste is counted in each $cm^2$ of the concrete section examined. In order to establish the impact of such a count on the variability of the test, when carried out by different operators, an exercise was proposed to the participants in the *DRI Workshop* to determine the number of cracks in the aggregate particle illustrated in the Figure 3A. Based on the method proposed by Sims et al. [11], the number of cracks in the above particle can be obtained by subtracting the number of *nodes* (10) from the total number of *crack segments* identified (22), which resulted in a total of 12 cracks (Figure 3B). The results of the exercise, given below, confirmed that the measurement of the number of cracks is a significant source of variability in the method.

- Min: 4 cracks
- Avg: 9 cracks
- Coeff. of variation: 56%
- Max: 18 cracks
- SD: 5 cracks

In order to reduce the above negative impact, a *Modified DRI Method (1)* (Table 1) was proposed where each aggregate particle (in each $cm^2$) is classified into one of two groups/categories, according to the number of internal cracks, i.e. particles with ≤ 2 cracks and particles with > 2 cracks. A similar "grouping" approach was also adopted for the count of the number of cracks in the cement paste, as well as the number of voids in the cement paste with reaction products (Table 1). Three types of cracks were recognized, both in the aggregate particles and in the cement paste:

- Closed/tight cracks (generally associated to aggregate processing (crushing) operations);
- Opened cracks or cracks forming a network, without reaction products;
- Cracks with reaction products.

Such a "grouping" approach required to establish additional rules for classifying cracked aggregate particles, as well as each $cm^2$ section of the cement paste containing cracks of different types (i.e. with and without reaction product). For instance, it was decided that the presence of at least one crack with reaction products in an aggregate particle, or in a $cm^2$ of the cement paste, would result in classifying the above in the categories *Particle/cement paste with reaction product*, in accordance with the number of cracks identified.

Weighing factors were attributed, in a logical but somewhat arbitrary manner, to each of the petrographic features in this *Modified DRI Method (1)* ("1st set" in Table 1). Identical factors were attributed to the two categories of opened cracks in the aggregate particles (2 or 4) or in the cement paste (4 or 6), with or without reaction products; this was done to reduce the variability associated to the difficulty in positively recognizing the presence of reaction products in cracks. Consequently, the two types of cracks could be grouped together (having the same weighing factors !), if one considers that a crack is an indication of damage, either with or without reaction products. Finally, larger weighing factors for cracks in the cement paste, compared to that in the aggregate particles, were selected to indicate that a greater importance is attributed to cracking in the cement paste, regarding the durability of the affected concrete element.

A new petrographic feature was also added in the *Modified DRI Method (1)*, i.e. desagregated/corroded aggregate particles; a weighing factor of 3 was attributed to that feature.

### 3.3 Laboratory investigations

Following the *DRI Workshop*, a first comparative study between the *Original DRI method* and the *Modified DRI method (1)* was organized at Laval University. Two polished laboratory concrete sections (VM1-R4, 0.066% concrete prism expansion; VM3-48, 0.176% concrete prism expansion), were selected and nine people with varying experience in DRI testing participated in the study. Prior to performing the petrographic examination of the polished sections, two 3-hour information sessions were held, where each petrographic feature of deterioration was described and illustrated, and differences between the two DRI procedures highlighted. In parallel to the comparative study, the two methods were applied to a number of polished concrete sections obtained from field structures and laboratory specimens (Table 2). The weighing factors proposed for the *Modified DRI method (1)* (1st set – Table 1) were then re-evaluated by comparison with the results of the *Original DRI method* (2nd set – Table 1). The results of the first comparative study were compiled, analyzed and changes were made to the *Modified DRI method (1)* in order to further reduce the variability between the operators. A *Modified DRI method (2)* was proposed and a second comparative study carried out. The results of the above laboratory investigations are presented and analyzed hereafter.

## 4. RESULTS AND DISCUSSION

### 4.1 Comparative study no. 1

The results of the first comparative study are presented in Table 1 (for each individual petrographic feature) and in Table 3 (for the different participants in the study). Fairly high coefficients of variation, i.e. ranging from 25 to 54%, were obtained for the two polished sections (Table 3). Despite information sessions, it appears that the main source of variability was the lack of experience of some of the operators. However, the coefficients of variation were found to decrease significantly from the *Original DRI method* to the *Modified Method (1)*, i.e. 54% to 35% for section VM1R-4 and from 35% to 25% for section VM3-48 (Table 3).

The detailed results presented in the Table 1 indicate that the petrographic features having a significant impact on the results and their variability (i.e. those with a large number of counts and high standard deviation / coefficient of variation values) correspond to *Opened cracks in the aggregate particles* and the various features involving the identification of reaction products both in the aggregate particles and in the cement paste (in cracks and in voids). The identification of reaction rims around reacted aggregate particles was also found to be a source of significant variation between the operators.

A post mortem meeting with the participants in the study revealed that a lack of proper definition of some of the features of deterioration, for instance "opened" crack in the aggregate particle or in the cement paste, caused some variations between the operators. Also, the use of a "grouping" approach for the various petrographic features, although it may have resulted in a significant reduction in the variation between operators (Table 3), was increasing the complexity and the time required for the examination of the sections.

### 4.2 Modification of the weighing factors in the *Modified DRI method (1)*

The *Original DRI method* and the *Modified DRI method (1)* were applied to a number of polished sections prepared from field and laboratory specimens involving a wide range of reactive rock types. The results, presented in Table 2 and illustrated in Figure 4, show that a reasonably good correlation exist between the two methods ($R^2$ of 0.87), despite the fact that *Modified DRI* values (using the 1st set of weighing factors) were generally significantly lower than those obtained from the *Original DRI method*. Based on the above results, a 2nd set of weighing factors was established using the same logical approach for the distribution of factors between the different types of petrographic features (Table 1). The correlation between the *Original DRI* and the *Modified DRI method (1)* (with the 2nd set of factors) values was found to improve slightly ($R^2$ of 0.91), while getting closer to the 1:1 line on the correlation graph (Figure 4).

### 4.3 Comparative study no. 2

Based on the results of the first comparative study, a *petrographic album* was developed, which defines and illustrates the features of deterioration in polished sections of different damage levels and incorporating different reactive aggregates [17]. The changes below were included in the *Modified DRI method (2)* (Table 4):

- The "grouping" approach for cracks in the aggregate particles was maintained since the comparative analysis of ASR-affected specimens revealed that the cracking patterns in the aggregate particles of concrete specimens subjected to laboratory testing was often more complex (and consequently a source of larger variability) than for field-type specimens;
- The "grouping" approach for cracks in the cement paste was abandoned as it appeared that they were not providing an adequate representation of their importance/weight in the overall damage of the samples;
- The "grouping" approach for voids with reaction products in the cement paste was abandoned;
- Identical weighing factors (2 and 4, with vs without reaction products) were attributed to cracks within the aggregate particles and in the cement paste.

A second comparative study was then organized (8 participants) using two polished sections from ASR-affected field structures (C-13 and T22-2; Table 2). The results of the second study are presented in the Table 4 (for each individual petrographic feature) and in Table 3 (for the different participants in the study). Despite the fact that a significant variability between operators, for some of the different petrographic features taken individually, was still noticeable (C.V. up to 70%, Table 4), lower coefficients of variation, ranging from 22 to 28%, were obtained in this 2$^{nd}$ comparative study (compared to the first one) (Table 3). Also, the coefficients of variation were found to be similar for one method to another (*Original DRI method* versus *Modified DRI method (2)*). The better results obtained in the 2$^{nd}$ comparative study are thought to be due to the improved experience of the participants and better defined petrographic features (particularly cracking in the aggregate particles).

One of the main sources of variation was the quantification of the number of voids with reaction products (Table 4). Since this feature is not really a feature of "damage" in the concrete, it was suggested to remove it from the counts in the DRI. This resulted in a significant reduction in the variability between operators, as can be seen from the numbers in brackets in the Table 3 (2$^{nd}$ comparative study); the coefficients of variation were indeed found to drop to 17-18%, which is considered very good for such a type of "subjective" test procedure.

## 5. CONCLUSIONS AND PROPOSED METHOD

The results obtained in this study indicate that the variability between the operators carrying out DRI testing can be significantly reduced by improving the definition of the different features of deterioration, and by appropriate training of petrographers using reference sections and well illustrated instructions.

Different quantitative approaches were evaluated in order to reduce the variability between the operators. The first one consisted in comparing the effect of determining, for each cm$^2$, the total <u>number of cracks</u> in each aggregate particle (*Original DRI method*) versus the <u>number of particles</u> with less or more than a specified number (2) of cracks (*Modified DRI method (1)*. It was found that similar results could be obtained from the two approaches when the weighing factors are adjusted accordingly; however, grouping the aggregate particles into classes did not contribute in reducing the variability between the operators while, from a practical point-of-view, it was found to increase the complexity and the time required for the test. Consequently, it is suggested to eliminate the "grouping" approach for the *cracking features* in the aggregate particles. Similarly, it was found preferable to count the total number of cracks within the cement paste (instead of grouping them into classes), since it results in a better representation of the overall damage in the concrete specimens. Eliminating the counts of the number of *voids with reaction products in the cement paste* and

*Reaction rims* from the calculation of the DRI values also contributes at reducing the variability between the operators in the DRI determination. This is acceptable considering that the above, despite being generally associated to ASR (when the nature/origin of the reaction products and of the reaction rim can be positively confirmed), are not really direct indications of "damage" in concrete. Finally, weighing factors of 2 or 3 were proposed for cracks in the aggregate particles and in the cement paste, respectively, with the presence or not of reaction products; as mentioned before, this is proposed to reduce the variability associated to the difficulty in positively recognizing the presence of reaction products in cracks.

Based on the above conclusions, a revised DRI method is proposed (Table 5), which generally support the approach originally proposed by Grattan-Bellew and colleagues [1-3]. Descriptions of the petrographic features are given in Table 5, while examples of such features are illustrated in Figure 1 and in a petrographic album [17]. Work is in progress at Laval University to try correlating the magnitude of the damage obtained from the DRI determination and the damage determined from other means (mechanical/physical testing) in concrete affected by ASR and other deleterious mechanisms.

## 6. REFERENCES


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TABLE 1: Petrographic features and weighing factors for the DRI, original method and modified method (1). The detailed results of the 1st comparative study are given (using the 1st set of weighing factors) for the two polished sections (VM1-R4 and VM3-48), i.e. the average number of counts (A), the standard deviation (SD) and the coefficient of variation in % (CV) for petrographic features with a significant number of counts.

<table>
<tr><th rowspan="2">Method</th><th rowspan="2" colspan="3">Petrographic features</th><th colspan="2">Weighing factors</th><th colspan="2">1st Comparative Study</th></tr>
<tr><th>1st set</th><th>2nd set</th><th>VM1-R4<br>A/SD(CV)</th><th>VM3-48<br>A/SD(CV)</th></tr>
<tr><td rowspan="8">Original DRI Method</td><td colspan="3">Cracks in coarse aggregate (CrCA)</td><td>0.25</td><td>--</td><td>466/118 (25)</td><td>390/163 (42)</td></tr>
<tr><td colspan="3">Opened cracks in coarse aggregate (OCrCA)</td><td>4</td><td>--</td><td>49/50 (102)</td><td>14/26 (184)</td></tr>
<tr><td colspan="3">Crack with reaction product in coarse aggregate (Cr+RPCA)</td><td>2</td><td>--</td><td>64/103 (163)</td><td>177/104 (59)</td></tr>
<tr><td colspan="3">Coarse aggregate debonded (CAD)</td><td>3</td><td>--</td><td>3/3</td><td>1/1</td></tr>
<tr><td colspan="3">Reaction rims around aggregate (RR)</td><td>0.5</td><td>--</td><td>57/65 (114)</td><td>59/89 (150)</td></tr>
<tr><td colspan="3">Cracks in cement paste (CrCP)</td><td>2</td><td>--</td><td>43/30 (70)</td><td>46/37 (80)</td></tr>
<tr><td colspan="3">Cracks with reaction product in cement paste (Cr+RPCP)</td><td>4</td><td>--</td><td>18/31 (171)</td><td>35/16 (47)</td></tr>
<tr><td colspan="3">Voids with reaction product in paste (RPAV)</td><td>0.5</td><td>--</td><td>106/130(122)</td><td>159/91 (57)</td></tr>
<tr><td rowspan="16">Modified DRI Method (1)</td><td rowspan="6">Number of aggregate particles with cracks</td><td rowspan="2">Closed/tight</td><td>≤2 cracks</td><td>0.5</td><td>1</td><td>90/36 (40)</td><td>91/48 (52)</td></tr>
<tr><td>>2 cracks</td><td>1</td><td>2</td><td>30/24 (82)</td><td>28/29 (103)</td></tr>
<tr><td rowspan="2">Opened or network (without react. prod.)</td><td>≤2 cracks</td><td>2</td><td>3</td><td>48/35 (73)</td><td>27/36 (134)</td></tr>
<tr><td>>2 cracks</td><td>4</td><td>5</td><td>28/23 (81)</td><td>9/13 (148)</td></tr>
<tr><td rowspan="2">Opened or network (with react. prod.)</td><td>≤2 cracks</td><td>2</td><td>3</td><td>19/20 (105)</td><td>67/27 (41)</td></tr>
<tr><td>>2 cracks</td><td>4</td><td>5</td><td>19/32 (167)</td><td>43/32 (76)</td></tr>
<tr><td rowspan="6">Number of cracks in the cement paste</td><td rowspan="2">Closed/tight</td><td>≤2 cracks</td><td>2</td><td>3</td><td>15/15 (100)</td><td>24/24 (98)</td></tr>
<tr><td>>2 cracks</td><td>3</td><td>4</td><td>2/4</td><td>1/2</td></tr>
<tr><td rowspan="2">Opened (without react. prod.)</td><td>≤2 cracks</td><td>4</td><td>6</td><td>16/4 (23)</td><td>11/7 (66)</td></tr>
<tr><td>>2 cracks</td><td>6</td><td>8</td><td>1/1</td><td>0/1</td></tr>
<tr><td rowspan="2">Opened (with react. prod.)</td><td>≤2 cracks</td><td>4</td><td>6</td><td>12/19 (161)</td><td>22/9 (40)</td></tr>
<tr><td>>2 cracks</td><td>6</td><td>8</td><td>2/4</td><td>3/3</td></tr>
<tr><td colspan="3">Number of debonded aggregate particles</td><td>2</td><td>5</td><td>3/3</td><td>1/1</td></tr>
<tr><td colspan="3">Number of particles with reaction rims</td><td>0.5</td><td>1</td><td>57/65 (114)</td><td>59/89 (150)</td></tr>
<tr><td colspan="2" rowspan="2">Number of voids in the cement paste with reaction product</td><td>≤4 voids</td><td>1</td><td>1</td><td>47/27 (58)</td><td>70/27 (39)</td></tr>
<tr><td>>4 voids</td><td>2</td><td>2</td><td>6/13</td><td>4/4</td></tr>
<tr><td colspan="3">Number of corroded aggregate particles</td><td>3</td><td>4</td><td>2/3</td><td>1/1</td></tr>
</table>

TABLE 2: Petrographic description of the reactive aggregates in the polished sections tested in the DRI. The sections used for the comparative studies are also identified, as follows: 1st study (A) and 2nd study (B).

| Type | Sample | Petro of aggregate (location) | Sample | Petro of aggregate (location) |
|---|---|---|---|---|
| Lab specimens | FHWA 45 | Greywacke (Pennsylvania, USA) | FHWA 33 | Quartzitic sandstone (South Dakota, USA) |
| | FHWA 21 | Gneiss, schists (Maryland, USA) | FHWA 87 | Greywacke (Massachusetts, USA) |
| | FHWA 105 | Granitic gneiss (Virginia, USA) | VM3-48[A] | Siliceous limestone (Ontario, Canada) |
| | FHWA 69 | Gravel (volcanics, quartzite, chert, greywacke) (Idaho, USA) | VM1R-4[A] | Siliceous/clayey limestone (Montreal region, Quebec, Canada) |
| | FHWA 111 | Gravel (granitic) (Wyoming, USA) | | |
| Field specimens | C13[B] | Gravel (greywacke, sandstone, granite) (bridge)(Ont., Canada) | ITD I84 PC8-4 | Polygenic gravel (volcanics, chert) (pavement)(Idaho, USA) |
| | T22-2[B] | Greywacke (highway barrier) (Massachusetts, USA) | S4 C2 | Quartzitic sandstone (pavement) (New Ulm, Minnesota, USA) |
| | MH 1B | Granite (Dam) (Manitoba, Canada) | RDQ | Polygenic gravel (granitic) (Dam) (Northern Quebec) |
| | BL | Greywacke (highway barrier wall) (Nova Scotia, Canada) | ZTT6-124 | Granite (Pavement) (Colorado, USA) |
| | HQ 2005 RDI P12 | Rapides des Iles (Dam) (Northern Quebec, Canada) | 5d | Polygenic gravel (volcanics) (pavement) (New Mexico, USA) |
| | D-113-5 | Gneiss, schists (pavement) (Delaware, USA) | 1A | Argilite / siltstone (bridge) (New Brunswick, Canada) |
| | DuVallon B1 | Siliceous limestone (bridge) (Quebec, Canada) | Potsdam | Sandstone (Dam) (Quebec, Canada) |

TABLE 3: Results of the comparative studies no. 1 (*Original DRI method* vs *Modified method (1)*) and no. 2 (*Original DRI method* vs *Modified method (2)*).

| Operator | Comparative Study no. 1 | | | | Comparative Study no. 2 (note 1) | | | |
|---|---|---|---|---|---|---|---|---|
| | VM1R-4 | | VM3-48 | | Sample C13 | | Sample T22-2 | |
| | Original method | Mod. Met. (1) | Original method | Mod. Met. (1) | Original method | Mod. Met. (2) | Original method | Mod. Met. (2) |
| 1 | 373 | 388 | 645 | 518 | 945 (542) | 868 (553) | 973 (456) | 887 (458) |
| 2 | 865 | 437 | 783 | 393 | 545 (542) | 457 (709) | 720 (446) | 585 (563) |
| 3 | 533 | 459 | 1093 | 738 | 1201 (897) | 1099 (736) | 969 (769) | 805 (557) |
| 4 | 479 | 280 | 771 | 467 | 1014 (660) | 931 (560) | 854 (563) | 755 (456) |
| 5 | 1154 | 691 | 1652 | 868 | 907 (640) | 842 (758) | 956 (564) | 783 (573) |
| 6 | 835 | 624 | 1078 | 712 | 1156 (713) | 1022 (827) | 1254 (566) | 1005 (566) |
| 7 | 1649 | 875 | 874 | 539 | 1192 (789) | 1077 (656) | 710 (658) | 537 (475) |
| 8 | 614 | 407 | 714 | 625 | 1025 (638) | 951 (486) | 535 (542) | 383 (328) |
| 9 | 413 | 535 | 680 | 707 | -- | -- | -- | -- |
| **Average** | **768** | **522** | **921** | **618** | **998 (678)** | **906 (661)** | **871 (570)** | **718 (497)** |
| Std Dev | 416 | 182 | 318 | 151 | 214 (121) | 203 (118) | 219 (105) | 202 (85) |
| **C of V (%)** | **54.1** | **34.9** | **34.5** | **24.5** | **22 (18)** | **23 (18)** | **25 (18)** | **28 (17)** |
| Minimum | 373 | 280 | 645 | 393 | 545 (542) | 457 (486) | 535 (446) | 383 (328) |
| Maximum | 1649 | 875 | 1652 | 868 | 1201 (897) | 1099 (827) | 1254 (769) | 1005 (573) |

Note 1 : The results in bracket correspond to DRI values once the counts for *Reaction products in voids of the cement paste* were removed from the calculations.

TABLE 4 : Petrographic features and weighing factors for the *Original DRI method* and the *Modified DRI method (2)* used for the 2nd comparative study. The detailed results of the 2nd comparative study are given for the two polished sections (C13 and T22-2), i.e. the average number of counts (A), the standard deviation (SD) and the coefficient of variation in % (CV) for petrographic features with a **significant** number of counts.

<table>
<tr><th rowspan="2">DRI Method</th><th rowspan="2" colspan="3">Petrographic features</th><th colspan="2">Weighing factor</th><th colspan="2">2nd Comparative Study</th></tr>
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<tr><td rowspan="3">Original</td><td colspan="3">Cracks in coarse aggregate</td><td>0.25</td><td rowspan="3"></td><td>79/32 (41)</td><td>91/57 (63)</td></tr>
<tr><td colspan="3">Open cracks in coarse aggregate</td><td>4</td><td>13/9 (72)</td><td>51/28 (55)</td></tr>
<tr><td colspan="3">Crack with reaction product in coarse agg.</td><td>2</td><td>52/16 (31)</td><td>85/30 (35)</td></tr>
<tr><td rowspan="6">Modified Method (2)</td><td rowspan="6">Number of cracked aggregate particles</td><td rowspan="2">Closed</td><td>≤ 2 cracks</td><td rowspan="6"></td><td>0.5</td><td>40/14 (35)</td><td>44/24 (55)</td></tr>
<tr><td>> 2 cracks</td><td>1</td><td>3/3</td><td>4/5</td></tr>
<tr><td rowspan="2">Opened/network (no react. prod.)</td><td>≤ 2 cracks</td><td>2</td><td>7/6</td><td>29/17 (57)</td></tr>
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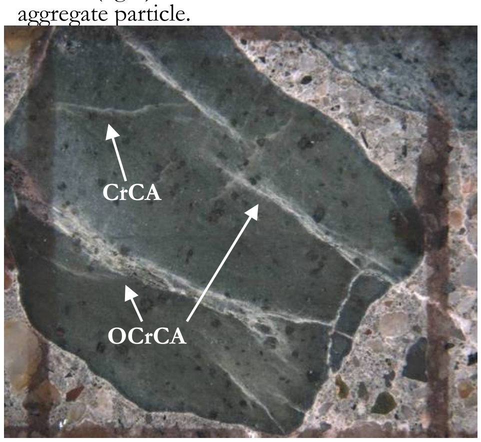
<tr><td rowspan="2">Opened/network (with react. prod.)</td><td>≤ 2 cracks</td><td>2</td><td>32/9 (27)</td><td>54/18 (34)</td></tr>
<tr><td>> 2 cracks</td><td>4</td><td>6/2</td><td>9/6</td></tr>
<tr><td rowspan="6">Features apply to both methods</td><td rowspan="2">Cracks in the C.P.</td><td colspan="2">Without reaction products</td><td>2</td><td>2</td><td>105/36(34)</td><td>48/15 (32)</td></tr>
<tr><td colspan="2">With reaction products</td><td>4</td><td>4</td><td>33/17 (52)</td><td>33/12 (36)</td></tr>
<tr><td colspan="3">Number of debonded aggregate particles</td><td>3</td><td>2</td><td>22/11 (49)</td><td>0/1</td></tr>
<tr><td colspan="3">Number of particles with reaction rims</td><td>0.5</td><td>0.5</td><td>107/34(32)</td><td>51/37 (73)</td></tr>
<tr><td colspan="3">Number of voids in the cement paste with reaction product</td><td>0.5</td><td>0.5</td><td>631/277 (44)</td><td>413/322 (78)</td></tr>
<tr><td colspan="3">Number of corroded aggregate particles</td><td>--</td><td>3</td><td>0/0</td><td>0/0</td></tr>
</table>

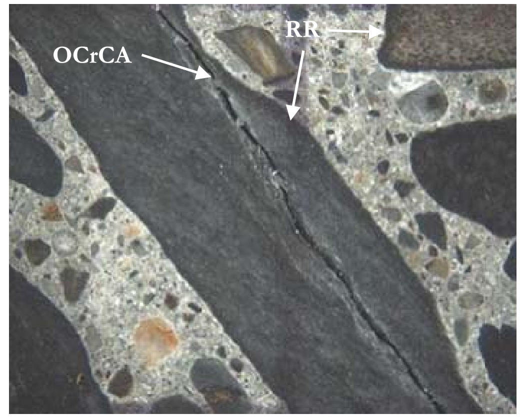
TABLE 5 : Petrographic features and weighing factors for the revised DRI method.

| Petrographic features | Factors | Comments |
|---|---|---|
| Closed/tight cracks in coarse aggregate particle | 0.25 | • Tight/fine cracks showing no gap at 16X magnification;<br>• Sometimes "appear" to contain whitish secondary products, as the crack forms an angle with the cutting plane (Fig. 1C, 1D).<br>• A low factor is given as such cracks are likely produced by aggregate processing operations (quarried aggregate) or weathering (gravel). |
| Opened cracks or network cracks in coarse aggregate particle | 2 | • Crack showing a gap at 16X magnification (Fig. 1B, 1F).<br>• A "network" of cracks (Fig. 1A) is also classified in this category as it is likely caused by expansive reactions within the aggregate particles. |
| Cracks or network cracks with reaction product in coarse aggregate particle | 2 | • Cracks containing secondary reaction products (whitish, glassy or chalky in texture) (Fig. 1D, 1E);<br>• Sometimes, the secondary products do not fill all the cracks (material lost during the preparation of the polished section (Fig. 1E)). |
| Coarse aggregate debonded | 3 | • Crack showing a <u>significant</u> gap in the interfacial zone between the aggregate particle and the cement paste (Fig. 1D);<br>• Would likely cause debonding of the particle when fracturing the concrete. |
| Disaggregated / corroded aggregate particle | 2 | • Aggregate particle that shows signs of disintegration, "corrosion" or disaggregation (ex: reacting opaline shale and chert/flint particles). |
| Cracks in cement paste | 3 | • Crack visible at 16X magnification (Fig. 1C), but with no evidence of reaction products. |
| Cracks with reaction product in cement paste | 3 | • Cracks containing secondary reaction products (whitish, glassy or chalky in texture) (Fig. 1D-1F);<br>• Sometimes, the secondary products do not fill all the cracks (material lost during the preparation of the polished section). |

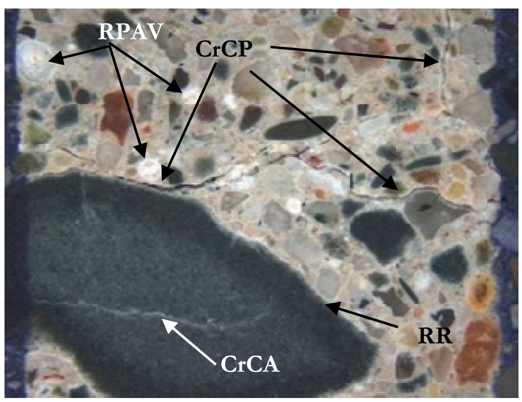
A : Closed (tight) cracks and network cracks in the aggregate particle.



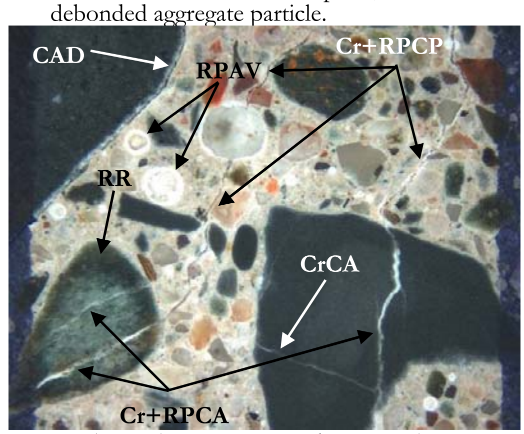

B: Open crack in the aggregate particle; reaction rims.



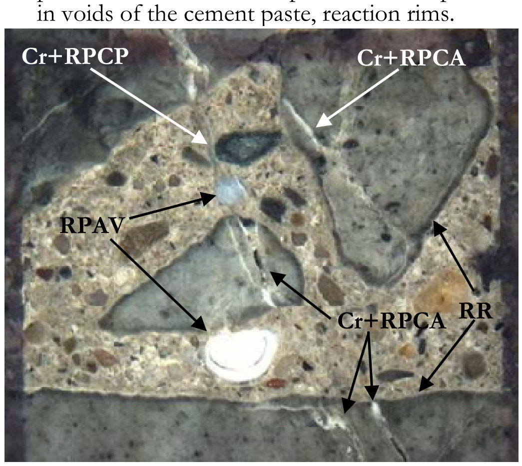

C : Tight crack in the aggregate particle; cracks in the cement paste; reaction products in air voids of the cement paste; reaction rim.




D: Cracks with reaction products in the aggregate particles and the cement paste; reaction product in air voids of the cement paste, reaction rims; debonded aggregate particle.




E : Cracks with reaction products in the aggregate particles and the cement paste; reaction product in voids of the cement paste, reaction rims.




F: Cracks with reaction products in the cement paste; opened cracks and cracks with reaction products in the aggregate particle.

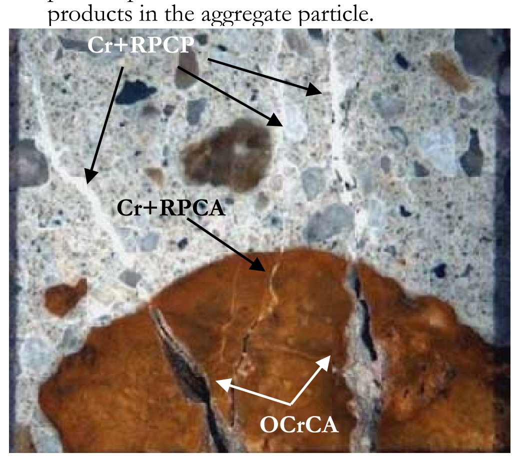



FIGURE 1 : Petrographic features of ASR in concrete; <u>the abbreviations are given in the Table 1 (*Original DRI Method*)</u>. The distance between the vertical lines is 1 cm.

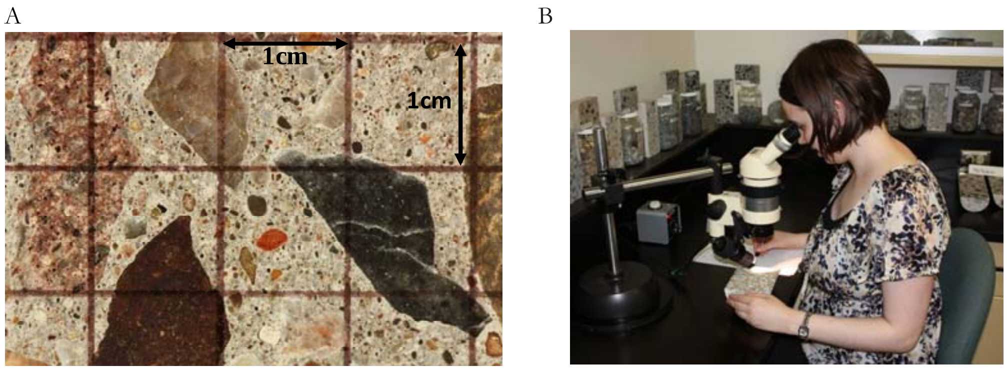



FIGURE 2. A. Grid drawn on the surface of a polished concrete specimen for DRI determination. B. Petrographic features and weighing factors for the DRI, according to [1].

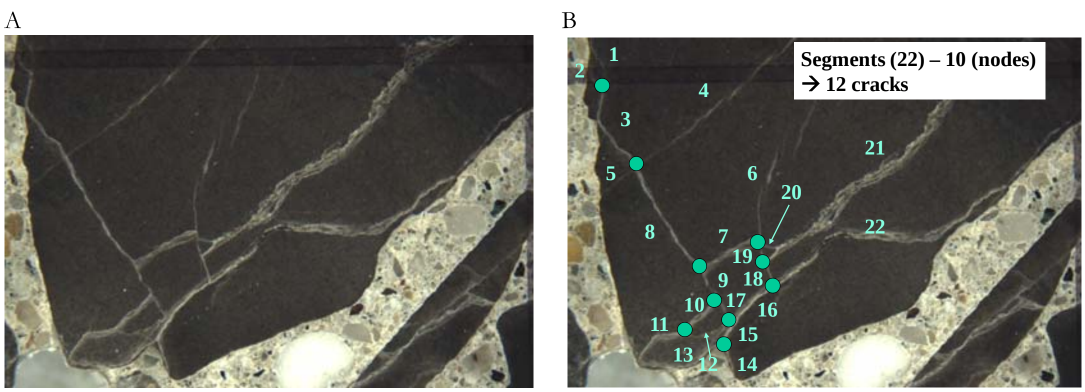



FIGURE 3. Exercise carried out to determine the number of cracks in the reactive aggregate particle.

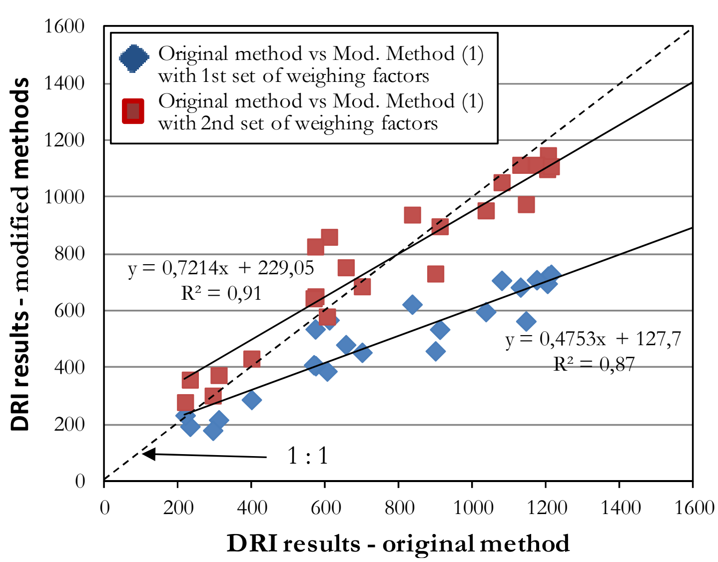



FIGURE 4 : Correlation between the results of the *Original DRI method* and the *Modified DRI method (1)* ($1^{st}$ and $2^{nd}$ sets of weighing factors – see Table 1)