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USING THE DAMAGE RATING INDEX FOR ASSESSING THE EXPANSION OF CONCRETE AFFECTED BY FREEZE-THAW, SULPHATE ATTACK, OR ASR

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Abstract

At various expansion levels due to ASR, freezing-thawing (FT) or delayed ettringite formation (DEF), the Damage Rating Index (DRI) was determined on laboratory concretes incorporating a highly-reactive limestone aggregate. For ASR, the DRI seems to be influenced by the w/c (lower DRI with a higher ratio) and the presence of air entrained (higher DRI). For similar expansion levels, the ASR-affected concrete presented much higher DRIs than the FT-damaged concrete, with the DEF-affected concrete far below. Very good linear relationships were obtained between the DRI and concrete expansion due to ASR ($R^2 \geq 0.92$) and FT ($R^2 = 0.95$), and a fairly good one for the DEF-affected concrete ($R^2 = 0.88$). However, the use of the DRI to assess the expansion due to DEF appears limited considering the relatively low DRI variations obtained (from 118 to 270) for the very large expansion range investigated (from 0 to 0.15%).

Keywords : alkali-silica reaction, concrete expansion, Damage Rating Index, freezing-thawing, delayed-ettringite formation

1 INTRODUCTION

The expansion attained to date by field concrete affected by ASR or by any other expansive mechanism is a crucial parameter in the evaluation of the structural integrity of the related structure, for instance to assess the degree of plasticity of the steel reinforcement [1] and for selecting the most appropriate repair techniques. In absence of in-situ monitoring since construction, one can try to relate the concrete expansion attained to in-situ cracking or to results from laboratory tests on cores, for instance the Stiffness Damage Test (SDT) and the Damage Rating Index (DRI) [2, 3, 4]. In this respect, Smaoui et al. [2] obtained very good relationships between ASR expansion and the results of SDT and DRI tests performed at various expansion levels on concretes incorporating a number of alkali-silica reactive aggregates.

This study concerns the DRI method, only. This method has been first proposed by Grattan-Bellew and Danay [5] for the evaluation of ASR-affected concrete. It is based on the determination by petrographic examination of the internal damage in concrete. Recently, Villeneuve [6] proposed a number of modifications to the method in order to improve its reproducibility.

This study was conducted through a M.Sc. research program [7]. It was principally initiated : (1), to determine the influence of freezing-thawing (FT) and delayed ettringite formation (DEF) on the DRI results, (2), to draw relationships between concrete expansion and this index, based on tests performed at different concrete expansion levels, and (3), to allow comparisons between the three different deterioration mechanisms investigated. At the same time, the effects of the w/c and air entrained were also investigated.

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2 MATERIALS AND METHODS

2.1 Materials

A coarse highly-reactive limestone from Québec City (Canada) and a non-reactive granitic sand from the same area were used for all 4 concrete mixtures tested (Table 1). Two CSA Type GU or ASTM Type I cements were used with Na_2O_{eq} contents of 0.82% (FT mix) and 1.25% (2 ASR mixes), respectively, and a CSA Type HE or ASTM Type III cement containing 1.30% Na_2O_{eq}, 3.6% SO_3, and 4.5% Al_2O_3 (DEF mix). Finely ground pure gypsum was added to the latter to attain 7.0% SO_3, thus a SO_3/Al_2O_3 of 1.7. An air-entraining admixture was used for the two ASR mixes to obtain between 5 and 7% air in the fresh concrete.

2.2 Concrete mixtures, test specimens and test conditions for ASR, FT, and DEF

For all mixtures, 100x200 mm cylinders were made with 420 kg/m^3 of cement, a coarse/fine aggregate of 60/40 by mass, and a w/c of 0.40 (ASR mix 1), 0.42 (FT and DEF mixes) or 0.48 (ASR mix 2) (Table 1). The two ASR mixes contained 5.25 kg/m^3 Na_2O_{eq}. All specimens were cured for 24 h in their mold. After demolding, metallic studs were fixed at both ends of all cylinders to allow axial length measurements. The specimens were then pre-cured at 23°C and 100% RH for 7 (ASR1), 10 (FT), 11 (ASR2) or 135 (DEF) days.

The air-entrained cylinders to be subjected to ASR were then stored upright above water at 38°C and >95% RH, in plastic pails (three specimens per pail). They were periodically measured hot for mass and axial length changes. After pre-curing, the non air-entrained cylinders to be damaged by FT were immersed in water until mass equilibrium (5 days), then placed in a freeze-thaw room allowing 24-h freezing-thawing cycles (in air) from +20°C to -16°C, i.e. 16-h freezing and 8-h thawing periods. They were periodically measured for mass and axial length changes, always at the end of thawing periods. After pre-curing, the non air-entrained specimens to be affected by DEF were subjected to a modified version of the Duggan test [8], described hereafter. For each concrete, at pre-selected expansion levels from 0 (zero) up to 0.20% (Table 1), one cylinder was taken out, dried at room conditions, then subjected to the DRI test described in Section 2.4.

2.3 Modified Duggan test

The Duggan test was first proposed for testing aggregates for potential ASR [8]. In this test, concrete cylinders, 22 mm ø by 50 mm long, are subjected to 3 cycles of wetting/drying, with wetting in distilled water at 23°C (for 3, 1, and 1 days), and drying in air at 80°C (for 1, 1, and 3 days), followed by continuous storage in distilled water at 23°C and periodic measurement for length change. The zero reading takes place one day after the final immersion, i.e. 11 days after the beginning of the test. Gabrowski et al. [9] demonstrated that the test was rather useful for determining the potential damage of concretes due to internal sulfate attack.

In this study, the test needed to be modified, based on a previous study [10], according to the larger size of the test cylinders to be tested (100-mm ø). The first three periods of immersion in water at 23°C were increased to 5, 5, and 13 days, respectively, to allow mass equilibrium before drying at 80°C. Moreover, to prevent any potential damage (cracking) due to thermal shock, before being returned in water, the cylinders were allowed to cool for 4 hours at room conditions after each drying period. Also, the first expansion reading was taken at the end of the first period of immersion, i.e. 5 days after the beginning of the test.

2.4 DRI test

As already mentioned, the DRI method is based on the determination by petrographic examination of the internal damage of concrete. It takes into account several defects related to the abundance and magnitude of characteristic signs of ASR, such as microcracks in reactive aggregate particles and in the cement paste (with or without secondary reaction products), dark reaction rims around reacted aggregate particles and alkali-silica reaction gel in air voids (Table 2). The observations are made on polished sections of concrete with a stereomicroscope at a 16X magnification. Each examined section is previously sectioned in square 1 x 1 cm units and the above magnification allows observing one 1 cm^2 unit at a time. A weighting factor is attributed to each defect observed according to its assumed contribution to the overall damage due to ASR (Table 2). The weighted sum of the defects is normalized to a surface of 100 cm^2 and the number obtained is called the "Damage Rating Index" or DRI.

The DRI was measured in conformity with Grattan-Bellew and Mitchell [11], as in the studies by Smaoui and co-workers [2, 3, 4]. Weighting factors of 0.75 and 4 were used for closed and open cracks in aggregates, respectively, rather than 0.25 for both (regrouped) types of cracks in the original method (Table 2). Once the desired expansion was attained, a thin slice of concrete was removed from each end of the 100 ø by 200 mm cylinder under study, to remove the metal studs used for axial length measurement. The residual cylinder was then cut lengthway in two halves. The DRI was measured on one of the two sections obtained, from 141 to 178 cm^2 [7], after polishing.

3 RESULTS

Figure 1 presents the expansion curve of the cylinder of each concrete mixture which was tested for DRI at the latest expansion level. ASR2, made with a higher w/c than for ASR1 (0.48 vs 0.40), looks slightly more rapidly expansive than ASR1. However, each curve in Figure 1 corresponds to only one cylinder, so the difference in expansion could be related to experimental variation.

Not surprisingly, no ASR-gel related defects are observed in FT and DEF concretes. The most important contributions to DRI (≥15%) are in red in the last 4 columns of Table 3. In the first column, the most contributing defects (≥15% for at least 2 of the 4 expansion levels >0.04%), are also in red.

Figure 2 shows the linear relationships between DRI and expansion. Statistics (regression coefficients R^2 and DRI intersects at 0% expansion) are given in Table 4. Very good relationships were obtained for the ASR ($R^2 \geq 0.92$) and FT ($R^2 = 0.95$) concretes, and a fairly good one for the DEF concrete ($R^2 = 0.88$).

Table 4 also presents statistics for the linear relationships between expansion and each individual defect. Values in red correspond to defects the most statistically-related to expansion ($R^2 > 0.65$). For each mixture, some defects are more contributing to the DRI, while being at the same time more statistically-related to concrete expansion (defects in red and bold in the first column of Table 3). Some other defects are just contributing significantly to the DRI (defects in red but not in bold in Table 3) or are just statistically-related to concrete expansion (defects in blue in Table 3).

4 DISCUSSION

4.1 Concretes affected by ASR

For each expansion level, the DRI for ASR2 is significantly lower than for ASR1, particularly at the two highest expansion levels considered. This is largely related to a much lower number of cracks with gel in aggregate particles, but just at these two levels, which thus appear doubtful. The number of air voids with gel is also considerably lower in ASR2, this time at each expansion level ; due to a higher w/c (0.48 vs 0.40), ASR2 is more porous and contains significantly more capillary pores. It could be that a greater proportion of the ASR-gel formed migrated through these pores, too small to be recognized in the DRI, thus leaving a relatively lesser amount of gel in the coarser air voids. ASR2 also differs from ASR1 as concerns : (1) debonded aggregate particles (more in ASR2, possibly due to a more porous/weaker paste-aggregate interface), (2) cracks with gel in the cement paste (more in ASR2), and (3) closed and open cracks in aggregate particles (ASR2 generally presenting more closed but less open cracks). However, the total number of all cracks in the cement paste is quite similar for the two mixes, Based on the results obtained, and their limited number, the effect of the w/c on the DRI results is not clear and more work is needed on this subject.

Surprisingly, at 0% expansion, reactions rims (38 and 32), debonded aggregate particles (11 and 6) and cracks (without gel) in paste (5 and 10) were abundant! The relatively high number of reactions rims at 0% expansion, also observed for the FT and DEF concretes, could be related to the particular aggregate used (limestone). There is also a lot of closed cracks in aggregate particles at 0% expansion due to ASR (125 and 116), and also for the FT (108) and DEF (104) concretes. This is likely due to the processing operations in the quarry (blasting, crushing, screening) before their use in concrete. Such cracks contributed significantly to the DRI but were clearly not statistically related to ASR concrete expansion (R^2 of 0.01 and 0.18).

In their experimental study, Smaoui et al. [2] also tested for ASR and DRI 100 x 200-mm cylinders made with the same aggregate and a w/c of 0.40. The only difference with the ASR1 concrete was the absence of air entrainment. Note that the DRI values reported by Smaoui et al. [2] were determined by the same person as in the present study [7]. The relationships obtained between the DRI and expansion were :

- Smaoui et al. [2] : DRI = 62.9 + 2738 x exp. (%) or Exp. (%) = (DRI – 62.9) / 2738 ($R^2 = 0.89$)
- This study : DRI = 73.3 + 6102 x exp. (%) or Exp. (%) = (DRI – 73.3) / 6102 ($R^2 = 0.96$)

For a given DRI, the expansion calculated using the latter relationship is about 2 times less than when using the first equation. At first, the results obtained in this study may suggest that air-entrained concrete presents greater DRI values than non-entrained concrete, at similar expansion levels. However, the large differences observed with the previous study were totally unexpected and, based on the limited number of experiments, more work is clearly needed on the effect of the air-entrainment on the DRI.

4.2 Concrete affected by freezing-thawing

As for all concretes, the high DRI value (185) at 0% expansion for the FT-affected concrete is related to numerous closed cracks in the aggregate particles (108), as expected, and to the relatively high numbers of reaction rims (45) and debonded aggregate particles (23), which are more questionable. For expansion levels >0.04%, it is interesting to note that, for this concrete, the total numbers of cracks in aggregate particles and of all cracks in paste are quite similar to those numbers for the ASR-affected concretes tested.

4.3 Concrete affected by sulfate attack

For the DEF-affected concrete, the most important contribution to DRI relates to the number of closed cracks in aggregates, which regularly increases with expansion, but which also always counts for 65 to 75% of the DRI. Cracks (without gel) in paste present the best linear relationship with expansion ($R^2 = 0.80$) but their number remains limited (14 at 0.20% expansion). Once again, the number of reactions rims is significant at 0% expansion (45) ! At first, the use of the DRI to assess the expansion due to DEF appears limited when considering the small DRI variations (118 to 270) obtained for the very large span of expansion investigated (0 to 0.15%), and the likely high interlaboratory variability in this test. It could be that most of the expansion attained by the DEF concrete, and by the FT concrete as well, is mostly related to microcracks that are too fine to be recognized in the DRI method, at the magnification used.

4.4 Using the DRI for assessing concrete expansion due to ASR, FT, and/or DEF

At the same expansion level, why the ASR concretes presented significantly higher DRI values than the FT concrete, with the DEF concrete being far below?. The response to the above question could be that some defects considered in the DRI are not relevant, and/or that important defects are missing, and/or that the weighting factors used are not appropriate, and/or that the defects generated by some deleterious mechanisms, for instance DEF and FT, are generating distresses that are undetected at the magnification used for the DRI. Let us recall that the principal objective of this study was to evaluate the possibility of using the DRI to estimate the expansion attained so far by concrete affected by ASR, FT and/or DEF, thus not the overall internal damage due to ASR-affected concrete.

In this respect, reaction rims and ASR gel or any other reaction product (e.g. ettringite) in cracks and air voids are an indication that chemical reactions took place in concrete and their abundance generally increases with the progress of the reactions involved and the associated expansion. However, these features are likely not a direct measure of the amount of expansion, compared with cracks for instance. Moreover, reaction rims were always quite abundant at 0% expansion, even for the FT and DEF concretes ; this is quite surprising for the quarried aggregate tested, despite also observed by Smaoui et al. [2]. Let us mention that both reaction rims and air voids with gel are not considered in the modified DRI method recently proposed by Villeneuve [6], however with the objective of improving the reproducibility of the test.

It is our opinion that the only defects useful for assessing the expansion attained so far by a damaged concrete, whatever the deterioration mechanism involved, are those related to the formation of additional discontinuities/voids of any type, i.e. to cracking and aggregate debonding, irrespective of the presence or not of reaction products in these voids. In other words, a crack with gel is an open crack which just contains gel. On the other hand, a significant number of closed cracks preexist in aggregates before any expansion, which greatly contribute to the DRI ; this number, however, should be considered since it also varies along with expansion, as particularly observed for the FT (R^2 = 0.94) and DEF (R^2 = 0.73) concretes tested. Unfortunately, the number of such pre-existing closed cracks is aggregate-dependent, as observed by Smaoui et al. [2], and may be influenced as well by the equipments used to produce aggregates. This is a serious limitation to our quest to develop an unique DRI-expansion calibration curve for assessing the expansion attained so far by concretes incorporating different types of aggregates, unless a correction is made based on petrographic examination.

4.5 Some attemps to improve the relationships between expansion and internal concrete damage

Based on the above discussion, a number of attempts have been made to improve the relationships between expansion and internal concrete damage, and to bring closer at the same time the results obtained for the three different expansion mechanisms investigated. Some results are given in Table 5.

Ignoring in the DRI calculation the defects not statistically-related to concrete expansion ($R^2 < 0.65$ in Table 4), either ignoring or not reaction rims and air voids with gel (cases 1 and 2 in Table 5), induced a positive or non-significant effect for the ASR2 and DEF concretes with respect to the relationship obtained with the original DRI values (i.e. R^2 increased, unchanged or decreased by ≤0.01 ; values in blue in Table 5). Just ignoring reaction rims and air voids with gel (case 3 in Table 5) was non-significant or positive for the ASR1 and FT concretes, however not for the two other ones. Still ignoring the above two defects and using a weighting factor of 3 for all cracks except closed ones in aggregates (case 4 in Table 5), was neutral or positive for mixes FT and DEF, particularly for the latter (R^2 from 0.88 to 0.95), while not for the ASR concretes. By giving more importance to cracks in paste (with gel or not), using a factor of 6 (case 5 in Table 5), was neutral or positive for all mixes (with respect to case 4), with again a greater effect for the DEF concrete (R^2 = 0.98).

Calculations were also made according to the modified DRI method recently proposed by Villeneuve [6] (case 6 in Table 5). In this method, reaction rims and air voids with gel are not considered (for reproducibility purposes), while the number of desaggregated aggregates is added (weighthing factor of 2). Moreover, modified weighting factors are proposed for closed cracks in aggregates (0.25), open cracks in aggregates (2), and 3 for both types of cracks in cement paste. The results obtained according to such proposals are not better than 4 of the 5 other trials above except for the DEF concrete (Table 5). It was not possible in the last calculation to take account for the number of desaggregated aggregates, a new defect just proposed ; however, the usual contribution of this defect to the overall DRI value remains relatively low [6].

Unfortunately, none of the modifications tested was capable of reducing the large differences observed in the DRI between the DEF concrete and the three other concretes tested.

5 CONCLUSIONS

Based on DRI determinations performed at different levels of expansion due to ASR (2 concretes), freezing-thawing (FT concrete) or internal sulfate attack (DEF concrete), on concrete cylinders made with a highly-reactive limestone aggregate, the following conclusions can be made :

- For similar expansion levels, the DRI results for the ASR concrete made with a w/c of 0.48 were always significantly lower than for the less porous ASR1 concrete, made with a w/c of 0.40.
- For similar expansion levels, the DRI results for the air-entrained ASR concrete made with a w/c of 0.40 was about two times higher than for a very comparable but non-air entrained concrete previously tested [2].
- Both ASR concretes presented significantly higher DRI values than the FT concrete, with the DEF concrete far below, always for similar expansion levels.
- Very good linear relationships were obtained between the DRI and concrete expansion due to ASR ($R^2 \geq 0.92$) and FT ($R^2 = 0.95$), and a fairly good one for the DEF concrete ($R^2 = 0.88$).
- The petrographic symptoms of concrete deterioration (or defects) the most-contributing to the DRI varied with the damaging mechanism involved, and the defects the most statistically-related to concrete expansion as well. Moreover, the most-contributing defects were not necessarily the most statistically-related to expansion, and the reverse is also true.
- Recalculations following a number of modifications related to the internal defects considered and their weighting factor, did not contribute to improve the relationships between DRI and concrete expansion, except for the DEF concrete, particularly by giving more importance to cracks in the cement paste. However, the results for this concrete remained always low with respect to the ASR and FT concretes tested, such as using the DRI to assess the expansion due to sulphate attack appears limited.
- It could be that a large proportion of the expansion attained by the DEF concrete, and by the FT concrete as well, at a lesser extent, is related to microcracks that are too fine to be recognized in the DRI method, at the magnification used.
- The overall results were rather disappointing as concerns the objective to develop an unique calibration curve to estimate the expansion attained so far by concrete affected by ASR, freezing-thawing, or internal sulfate attack, particularly when considering that some artefacts (e.g. closed cracks in aggregates) are aggregate-dependent and that the DRI could be also affected by air-entrainment and the w/c as well. However, more work is needed to confirm the actual effect of the two latter parameters on the DRI.

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TABLE 1 : Characteristics of concrete mixtures, test specimens, and testing conditions.

Parameter	**ASR mix 1**	**ASR mix 2**	**FT mix 3**	**DEF mix 4**
Water/cement	0.40	0.48	0.42	0.42
Cement (%Na_2O_{eq})	1.25		0.82	1.30 + gypsum
Air entrained (%)	5.7 (AEA)	7.0 (AEA)	1.8 (no AEA)	2.6 (no AEA)
Test conditions	above water in sealed plastic pails at 38°C and >95% RH		24-h freezing-thawing cycles (+20/-16°C)	3 cycles of wetting in distilled water at 23°C (5, 5, 13 d) and drying in air at 80°C (1, 1, 3 d), then continuous storage in water at 23°C
Expansion levels for DRI tests (%)	0, 0.043, 0.082, 0.125, 0.156	0, 0.042, 0.078, 0.118, 0.160	0, 0.045, 0.094, 0.135, 0.198	0, 0.045, 0.076, 0.115, 0.152

TABLE 2 : Defects considered in the DRI method and associated weighting factors.

Defects	**Weighting factors**		
	Original method [5]	**Grattan-Bellew and Mitchell [11] (this study)**	**Villeneure [6] (new modified method)**
Closed cracks in aggregate particles	x 0.25 (grouped)	x 0.75	x 0.25
Open cracks in aggregate particles		x 4	x 2
Cracks with gel in aggr. particles	x 2	x 2	x 2
Debonded aggregate particles	x 3	x 3	x 3
Reaction rims around aggr. particles	x 0.5	x 0.5	Not considered
Cracks in cement paste	x 2	x 2	x 3
Cracks with gel in cement paste	x 4	x 4	x 3
Air voids with gel	x 0.5	x 0.5	Not considered
Desaggregated aggregate particles	Not considered	Not considered	2

TABLE 3 : DRI results and contributions of each defect before application of the weighting factors [a].

ASR Mix 1, W/C = 0.40 (air-entrained)					
Number of defect/100 cm² Expansion →	**0.000%**	**0.043%**	**0.082%**	**0.125%**	**0.156%**
Closed cracks in aggregate particles (0.75)	125 (59)	198 (55)	279 (44)	236 (20)	120 (9)
Open cracks in aggregates (4)	1 (0)	4 (6)	6 (6)	21 (9)	40 (15)
Cracks with gel in aggregate particles (2)	0	20 (15)	34 (14)	191 (44)	254 (48)
Debonded aggregate particles (3)	11 (21) ?	5 (6)	9 (6)	6 (2)	7 (2)
Reaction rims around aggregate particles (0.5)	38 (12) ?	65 (12)	62 (7)	63 (4)	80 (4)
Cracks in cement paste (2)	5 (7) ?	8 (6)	14 (6)	30 (7)	19 (4)
Cracks with gel in cement paste (4)	0	0	4 (4)	13 (6)	18 (7)
Air voids with gel (0.5)	0	3 (1)	131 (14)	145 (8)	267 (13)
Damage Rating Index (DRI)	**160**	**271**	**472**	**877**	**1063**

ASR Mix 2, W/C = 0.48 (air-entrained)					
Number of defect/100 cm² Expansion →	**0.000%**	**0.042%**	**0.078%**	**0.118%**	**0.160%**
Closed cracks in aggregate particles (0.75)	116 (57)	104 (46)	102 (16)	90 (9)	158 (16)
Open cracks in aggregate particles (4)	3 (8)	4 (9)	22 (19)	45 (25)	60 (32)
Cracks with gel in aggregate particles (2)	0	22 (25)	67 (28)	99 (28)	34 (9) ?
Debonded aggregate particles (3)	6 (12) ?	4 (8)	20 (13)	17 (7)	31 (12)
Reaction rims around aggregate particles (0.5)	32 (10) ?	32 (9)	41 (4)	64 (5)	87 (6)
Cracks in cement paste (2)	10 (13) ?	1 (1)	6 (3)	10 (3)	18 (5)
Cracks with gel in cement paste (4)	0	1 (1)	14 (12)	29 (17)	27 (15)
Air voids with gel (0.5)	0	2 (1)	45 (5)	84 (6)	97 (6)
Damage Rating Index (DRI)	**152**	**172**	**471**	**707**	**757**

FT Mix 3 (non air-entrained)					
Number of defect/100 cm² Expansion →	**0.000%**	**0.045%**	**0.094%**	**0.135%**	**0.198%**
Closed cracks in aggregate particles (0.75)	108 (44)	171 (45)	177 (40)	206 (40)	244 (31)
Open cracks in aggregate particles (4)	0	14 (20)	5 (6) ?	18 (18)	26 (18)
Cracks with gel in aggregate particles (2)	0	0	0	0	0
Debonded aggregate particles (3)	23 (37) ?	14 (15)	30 (27)	19 (15)	46 (24)
Reaction rims around aggregate particles (0.5)	45 (12) ?	44 (8)	54 (8)	55 (7)	62 (5)
Cracks in cement paste (2)	6 (7) ?	19 (13)	31 (19)	39 (20)	65 (22)
Cracks with gel in cement paste (4)	0	0	0	0	0
Air voids with gel (0.5)	0	0	0	0	0
Damage Rating Index (DRI)	**185**	**288**	**330**	**387**	**586**

DEF Mix 4 (non air-entrained)					
Number of defect/100 cm² Expansion →	**0.000%**	**0.045%**	**0.076%**	**0.115%**	**0.152%**
Closed cracks in aggregate particles (0.75)	104 (66)	165 (75)	215 (74)	173 (65)	239 (67)
Open cracks in aggregate particles (4)	4 (12)	2 (4)	4 (6)	1 (1)	4 (6)
Cracks with gel in aggregate particles (2)	0	0	0	0	0
Debonded aggregate particles (3)	1 (3)	0	0	4 (5)	2 (2)
Reaction rims around aggregate particles (0.5)	45 (19) ?	67 (20)	84 (19)	69 (17)	78 (15)
Cracks in cement paste (2)	0	1 (1)	1 (1)	12 (12)	14 (10)
Cracks with gel in cement paste (4)	0	0	0	0	0
Air voids with gel (0.5)	0	0	0	0	0
Damage Rating Index (DRI)	**118**	**165**	**218**	**201**	**270**

[a] Sign ? correspond to doubtful or unexpected values. Results are in number of defects/100 cm², but contributions in % to the DRI are given between brackets. For each expansion level, significant contributions to the DRI (>15%) are in red. For each concrete, defects in red (either in bold or not) are contributing significantly to the DRI (>15% for at least two of the 4 expansion levels >0.04%) ; defects in red and in bold are also statistically-related to concrete expansion (see Table 4 : $R^2 \geq 0.65$) ; for their part, defects in blue are statistically-related to concrete expansion, however not contributing significantly to the DRI.

TABLE 4 : Linear relationships between concrete expansion and DRI and each individual defect[a].

Defects (x weighting factors)	ASR mix 1			ASR mix 2			FT mix 3			DEF mix 4		
	R^2	Y0 [b]	Sl. [c]	R^2	Y0 [b]	Sl. [c]	R^2	Y0 [b]	Sl. [c]	R^2	Y0 [b]	Sl. [c]
Closed cracks in aggregates (x 0.75)	0.01	137	+	0.18	75	+	0.94	91	+	0.73	91	+
Open cracks in aggregates (x 4)	0.83	-20	+	0.94	-17	+	0.72	7	+	0.00	11	-
Cracks with gel in aggregates (x 2)	0.86	-79	+	0.33	32	+						
Debonded aggregates (x 3)	0.26	28	-	0.82	9	+	0.50	47	+	0.25	1	+
Reaction rims around aggr. (x 0.5)	0.72	23	+	0.89	11	+	0.93	22	+	0.54	27	+
Cracks in cement paste (x 2)	0.68	10	+	0.39	8	+	0.98	10	+	0.80	-5	+
Cracks with gel in cement paste (x 4)	0.90	-12	+	0.87	-10	+						
Air voids with gel (x 0.5)	0.89	-14	+	0.93	-5	+						
Damage Rating Index (DRI)	0.96	73	+	0.92	103	+	0.95	178	+	0.88	124	+

[a] Values in red correspond to defects the most statistically-related to concrete expansion ($R^2 > 0.65$).
[b] DRI value at 0 expansion, calculated from the linear relationship obtained between expansion and the DRI.
[c] Slope of the linear relationship : sign + means that the defect increases with expansion, with the reverse for sign -.

TABLE 5 : DRI* calculated according to modifications to the defects retained and their weighting factors.

ASR Mix 1 (w/c = 0.40) Expansion ➔	**0.000%**	**0.043%**	**0.082%**	**0.125%**	**0.156%**	**R^2 [a]**	**Y0 [a]**
All defects (original DRI values)	160	271	472	877	1063	0.96	73
1. Only defects statistically-related to expansion	32	107	234	682	952	0.91	-91
2. Same but minus reaction rims and air voids with gel	13	73	138	578	779	0.88	-100
3. All defects except reaction rims and air voids	141	237	375	774	890	0.94	65
4. Same but factor 3 for all cracks except closed/aggr.	146	261	413	960	1105	0.93	38
5. Same but factor 6 for all cracks in paste	162	286	467	1090	1215	0.93	44
6. Modified DRI method proposed by Villeneuve [6]	82	138	233	631	751	0.91	-9
ASR Mix 2 (w/c = 0.48) Expansion ➔	**0.000%**	**0.042%**	**0.078%**	**0.118%**	**0.160%**	**R^2 [a]**	**Y0 [b]**
All defects (original DRI values)	152	172	471	707	757	0.92	103
1. Only defects statistically-related to expansion	45	48	249	422	535	0.94	-11
2. Same but minus reaction rims and air voids with gel	29	31	206	348	443	0.94	-17
3. All defects except reaction rims and air voids	136	155	428	633	665	0.91	97
4. Same but factor 3 for all cracks except closed/aggr.	143	173	465	667	629	0.86	124
5. Same but factor 6 for all cracks in paste	173	178	524	784	765	0.87	128
6. Modified DRI method proposed by Villeneuve [6]	82	96	324	479	456	0.86	62
FT mix 3 Expansion ➔	**0.000%**	**0.045%**	**0.094%**	**0.135%**	**0.198%**	**R^2 [a]**	**Y0 [b]**
All defects (original DRI values)	185	288	330	387	586	0.95	178
1. Only defects statistically-related to expansion	117	246	240	329	448	0.94	131
2. Same but minus reaction rims and air voids with gel	94	223	213	302	417	0.93	109
3. All defects except reaction rims and air voids	162	266	303	360	555	0.95	156
4. Same but factor 3 for all cracks except closed/aggr.	169	271	329	381	595	0.95	159
5. Same but factor 6 for all cracks in paste	188	328	422	496	792	0.96	175
6. Modified DRI method proposed by Villeneuve [6]	115	171	236	260	448	0.93	97
DEF mix 4 Expansion ➔	**0.000%**	**0.045%**	**0.076%**	**0.115%**	**0.152%**	**R^2 [a]**	**Y0 [b]**
All defects (original DRI values)	118	165	218	201	270	0.88	124
1. Only defects statistically-related to expansion	78	125	162	153	207	0.91	85
2. Same but minus reaction rims and air voids with gel	78	125	162	153	207	0.91	85
3. All defects except reaction rims and air voids	95	132	176	166	230	0.90	97
4. Same but factor 3 for all cracks except closed/aggr.	92	131	173	177	241	0.95	91
5. Same but factor 6 for all cracks in paste	92	132	175	212	283	0.98	83
6. Modified DRI method proposed by Villeneuve [6]	36	46	62	90	117	0.96	28

[a] R^2 : regression coefficient for the relationship DRI* vs expansion ; Y0 : DRI* calculated at 0% expansion. Values in blue indicate a positive or a non-significant effect with respect to the relationship obtained using the original DRI values (i.e. R^2 increased, unchanged or decreased by ≤ 0.01) ; values in red indicate a negative effect (i.e. R^2 decreased by >0.01).

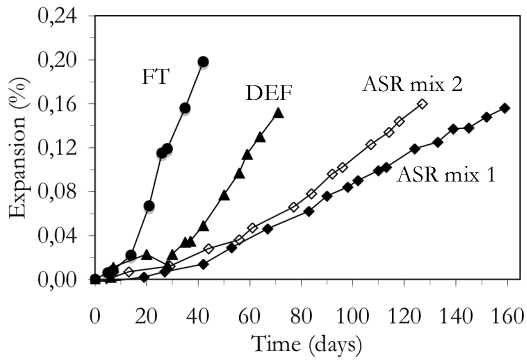

FIGURE 1 : Expansion of the cylinder of each mix which was tested for DRI at the latest expansion level.

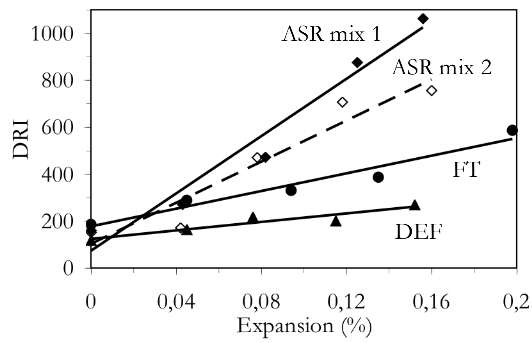

FIGURE 2 : Linear relationships obtained between concrete expansion and the DRI.