RESIDUAL EXPANSION TESTING: NEW ASPECTS ON CORES EXTRACTED FROM EXPOSURE BLOCKS SUBMITTED TO ENVIRONMENTAL CONDITIONS

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Abstract

Residual expansion testing on cores in the laboratory is intended to provide an estimate of the future expansion in an AAR-affected structure, thus helping engineers to take appropriate remedial measures for aging concrete structures. However, rare data are available that confirm the reliability of the laboratory test. In an attempt to generate that information, concrete blocks incorporating a selection of reactive aggregates were cast and placed outdoors at the University of Texas exposure site in Austin. Expansion measurements were taken regularly to ensure coring at preselected expansion levels (i.e., from 28 days to 0.40%). Residual expansion tests were then carried out on two companion concrete cores (100 x 200mm) for each reactive aggregate and expansion levels. In order to better correlate the expansion rates and total expansion of the exposure blocks and of the concrete cores, the preconditioning period of the lab specimens (for hydric reequilibration) was fixed at 14 days for ASR-affected concretes and 7 days for ACR-affected concrete. The results obtained so far indicate that the core expansion test in the laboratory generally underestimates the values encountered in the field. Factors were however suggested to better correlate field and laboratory data and that could be used by engineers to develop various scenarios for the prognosis of expansion in the field.

Keywords: alkali leaching, core testing, residual expansion, specimen size

1 INTRODUCTION

1.1 Diagnosis and prognosis of ASR in concrete infrastructure

In an attempt to extend the service life of concrete infrastructures and to implement appropriate repair strategies, engineers need to identify the probable deterioration causes, the current condition of these infrastructures and their potential for further deterioration. A petrographic examination carried out on cores taken from a deteriorated structure generally allows to identify the presence (or not) of AAR (*Diagnosis*). However, only a few techniques permit the determination of the actual condition and the risk for further damage (*Prognosis*). This is particularly critical for AAR affected structures because very few repair techniques are efficient while the reaction is still active. In fact, the difficulty is that the concrete behaviour in the tests (and then the evaluation of the current concrete condition) is strongly influenced by the reactive aggregate type, which requires to better understand the reaction mechanisms.

When premature or unexpected signs of deterioration are first identified from the visual survey of concrete structure, the common practice is to submit a series of cores extracted from the above structure to compressive strength tests. However, when AAR is identified as the primary cause of distress, this approach rarely provides satisfactory results because the reaction generally does not affect the compressive strength until the concrete has undergone a high level of damage/expansion. Several methods of *damage* evaluation[1] have been proposed for AAR affected concrete structures, such as the *Stiffness Damage Test (SDT)* [1-4], petrographic examination including *Damage Rating Index (DRI) and image analysis* [5-7], *Surface Cracking measurements* [3,4], and so on. However, in AAR-affected structures, it is also critical to determine the residual expansion because the current condition/damage is only a picture at a precise moment in time considering the evolution of the reaction.

1.2 Residual expansion testing

The Residual Expansion Test (RET) performed on cores is intended to generate a fair estimate (prognostic) of the future condition (expansion) of an AAR affected structure, especially when coupled with other prognostic techniques (such as the soluble alkalis determination by the Hot Water Extraction method [3,4]). The most commonly used residual expansion test consists at measuring periodically, over a one-year period, the mass and dimensional changes of cores taken from a problematic structure while maintained in conditions promoting the development of AAR in the laboratory (38°C and R.H. > 95%)[3,4]. The data thus obtained allow to estimate the expansion rate and the potential for total expansion that the structure may suffer, given that conditions necessary for AAR are maintained.

2 SCOPE OF WORK

The results presented in this paper are part of a larger project intended to develop efficient and reliable testing protocol for the early detection of ASR in concrete structures, the determination of the current damage condition (*diagnosis*) and the potential for further expansion of concrete affected by ASR (*prognosis*). The specific objective of this testing program is to determine to what extent the testing of cores in well-controlled but accelerated test conditions can be used to determine/estimate the potential for further expansion of concrete affected by alkali-silica and alkali-carbonate reactions.

3 MATERIALS AND METHODS

A variety of alkali-silica reactive (New Mexico gravel (Placitas), Jobe sand, Massachusetts greywacke, Minnesota quartzite and Spratt limestone) and alkali-carbonate reactive (Kingston limestone) aggregates have been used in the manufacture of concrete blocks, 400 x 400 x 700 in size, that were subjected to natural environmental conditions in Texas (to accelerate the damage generated by AAR)[8](Figure 1). The concrete mixtures were made in accordance with ASTM C 1293 requirements (cement content 420 kg/m^3, alkalis boosted to 1.25% Na_2Oeq). Cores were extracted from these blocks at selected expansion levels (28 days to 0.40%) and submitted to several non-destructive and destructive (e.g. mechanical, petrographic) tests. Residual expansion testing was conducted in accordance with the procedure described by Fournier et al. [4], which consisted in subjecting cores, 100 x 200 mm, to expansion test in air at > 95% R.H. and 38°C (100°F) (Figure 2A). The mass variations and longitudinal changes of the core samples were monitored over the one-year test period.

4 RESULTS

Table 1 gives the basic data and the results of the different calculations used to determine the total expansion and the expansion rates of the cores. The core expansion curves are illustrated in Figures 4 to 7.

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[1] In this study, the term *Damage* refers to measurable consequences of various processes/mechanisms (e.g. stresses, shrinkage, creep, AAR, freeze-thaw, sulphate-attack, etc.) on the physical integrity and the properties/performance (mechanical, in durability) of concrete.

In the first few weeks of testing, the cores are experiencing different processes concurrently, i.e. hydric reequilibration and AAR expansion. The magnitude and the time duration of the hydric reequilibration will depend on whether the cores have dried significantly following extraction. To ensure that the expansion due to hydric reequilibration is eliminated from the calculations of the residual expansion, Bérubé et al. [9] proposed to start considering the residual expansion behaviour of the cores when the mass gain of the latter have reached a plateau (Figure 2B). Tests performed in this research project have however shown that this may likely result, in some cases, in the elimination of some AAR-related residual expansion. According to the results obtained in this research project (Table 2), a significant proportion of the hydric reequilibration took place within the first two weeks of the test (and even in the first week for Kingston limestone)(Figure 1). In order to optimize the residual expansion testing period, the hydric reequilibration periods were thus fixed at 14/15 days for ASR aggregates (Figures 3A-3C) and 7 days for the Kingston aggregate (Figure 3D).

Based on the above predeterminated hydric reequilibration periods, the total expansion *(Tmax)* (ASR reactive aggregates only) was then calculated by subtracting the maximal core expansion (flattening of the curves) from the expansion value at the end of the selected hydric reequilibration period (*T0*) (14 days-ASR); this allowed for the calculation of the *residual expansion rate* of the cores, which was normalized on an annual basis (*Rate (%/yr))*. In the case of the Kingston reactive limestone (ACR), the rate calculations were slightly modified. As seen in figure 4, the expansion curves show two phases, a main phase characterized by a high expansion rate, which progressively decreases to enter in a second phase where the rate is much lower but still active until the end of the one-year testing period. It is from the first break in the slope of the expansion curve (where the rate starts to diminish) that the rate calculation was stopped according to our modifications.

Table 1 also gives the values of the *Rate of block expansion at the time of coring*, which was calculated from the expansion curves of the exposure blocks. A comparison of the calculated expansion rate according to Bérubé et al. [9] and according to technique proposed in this study is shown in Figures 4 to 7.

4.1 Jobe reactive sand

In the case of the Jobe cores (Figure 4A), similar expansion rate values, i.e. ranging from 0.27 to 0.35%/yr, were obtained for the cores extracted from the *0.04%* to *0.28%* concrete blocks; the rate value then dropped significantly (0.07%) for the *0.41% block* (Table 1). The values of the total residual expansions (*Total value (%)* in Table 1) showed about the same trends, i.e. the maximum value (>0.21) being obtained for the cores extracted from the *28 days block* and the lowest total residual expansion value (0.028%) obtained for the *0.41% block*. This confirms that the test is sensitive to the degree of reactivity/expansion/damage that has already occurred in the concrete prior to the extraction of the cores. The maximum core expansions were obtained after about 170 days of testing (levelling off most likely due to alkali leaching).

4.2 New Mexico gravel (Placitas) and Massachusetts greywacke

In the case of the NM (Placitas) and Mass cores (Figures 5A and 6A), core expansion rates were found to be fairly similar for the cores extracted from the *0.04%* to *0.20%* concrete blocks. The total residual expansion was found to decrease with increasing concrete block expansion levels, probably due to consumption of alkalis through the ASR process in the exposure blocks prior to the testing of the cores in the laboratory. The maximum core expansions were obtained after about 170 days (New Mexico) and 140-210 days (Massachusetts) of testing (levelling off most likely due to alkali leaching).

4.3 Kingston Limestone (RAC)

The Kingston cores showed a significantly different behaviour (Figure 7A). The residual expansion rates were found to increase with increasing block expansion levels (Table 1), while the expansion of the cores had not levelled off after 419 days of testing, despite significant leaching of concrete alkalis which has most likely caused the expansion to level off after about 150 days of testing with the other aggregates.

5. DISCUSSION

Table 3 and figures 4B to 7B compare the expansion rates calculated from the exposure blocks and from the concrete cores, both at the selected block expansion levels. For laboratory specimens, comparisons are illustrated in Figures 4B to 7B for the calculated expansion rates according to Bérubé et al. [9] and according to the approach proposed in this study. At first glance, the above results suggest that there is no direct correlation between the rate of expansions of the concrete blocks and that of the cores in the accelerated test conditions. This was expected, to some extent, considering the differences in the nature (blocks vs cores) and exposure conditions (natural environment vs 38°C, R.H.> 100%) of the test specimens.

The expansion rates based on the methods proposed by Bérubé et al. [9] and the approach used in this study were fairly similar for all alkali-silica reactive aggregates tested (solid short line vs dotted short lines in Figures 4B - Jobe, 5B - New Mexico gravel (Placitas) and 6B - Massachusetts); they were however significantly lower than those calculated from the concrete block expansions in the field (and illustrated in the figures 2B to 5B), except perhaps in the case of the Massachusetts aggregate (Figure 6B, block expansion levels 0.05% and 0.09%). The expansion rates calculated from the core expansion of the Kingston limestone, with the 7-day hydric reequilibration period (as proposed in this study), were however found to reproduce fairly well those of the exposure blocks (solid short lines vs expansion curve of the blocks in Figure 7B).

Table 3 proposes a series of multiplication factors that could potentially be used for estimating the expansion rates observed in the field concrete specimens based on the expansion rates calculated from the core expansions in laboratory test conditions. The above factors range from 2 to 4 to 5 to 10, according to the reactive aggregate. It is interesting to note that the multiplying factors increase with increasing reactivity level of the aggregate; being the highest (5 to 10) for the extremely reactive Jobe sand and moderate (2 to 5) for the highly reactive New Mexico gravel (Placitas) and Massachusetts greywacke. The rates are not provided for the Kingston limestone since the expansions are still in progress and it seems to be a fairly unique/particular case.

6. CONCLUSION

The best approach to determine expansion rates and of the total residual expansion in AAR-affected structures remains the in-situ monitoring of the field structure since it gives information directly correlated with local conditions (environment, stress states within/between the affected elements, etc.). This kind of data however takes years to establish in the field and are not commonly available to engineers. Consequently, alternative solutions have been proposed, the most commonly used being the testing of cores extracted from AAR-affected structural element(s) in laboratory conditions, generally 38°C and R.H. > 95%. In an attempt to develop further information on the reliability of the laboratory expansion test, a series of concrete blocks, 400 x 400 x 700 mm, in size were made with six reactive aggregates and placed outdoors for expansion monitoring in Texas. At selected expansion levels (ranging from 28 daysto 0.40%), 100mm-diameter cores were extracted from the blocks and subjected to laboratory testing. The longitudinal expansion and weight changes of the cores (testing at 38°C and R.H. > 95%) were monitored over a minimum one-year period.

The values of total "residual" expansion and expansion rates calculated from the core expansions were found to be affected by the moisture condition of the test specimens, i.e. whether or not the core was allowed to dry significantly before the start of the test. The selection of the hydric reequilibration period may vary according to the approach adopted. In any case, the monitoring of mass gain of the test cores is an important element of the test program and contributes to the selection of the residual expansion period.

The results obtained so far in this study indicate that the core expansion test in the laboratory generally underestimates the values encountered in the field. This was expected as the exposure block expansion rates are related to the local environmental conditions. However, we were able to establish some multiplying factors that could be used for estimating the field expansions based on laboratory test results. The above factors were found to vary, at least partially, according to the reactivity level of the aggregate. They could be used to establish a series of scenarios, that could vary from optimistic (e.g. factor of 2 to 4x) to pessimistic (factor up to 10x), in the process of determining the potential for further expansion of the AAR-affected element. Regarding the potential for determining the total residual field expansion based on the core expansions, it is too early to conclude since the exposure blocks in the field have not reached their final expansion yet. However, it appears that this will be a challenge considering the huge drawback of laboratory testing conditions, which promote the rapid leaching of alkalis from the core specimens, thus resulting in the premature levelling of the expansion curves. In order to reduce the impact of alkali leaching from the test cores, Fournier et al. [4] suggested using 150 x 300 mm cores instead of the usual 100 mm cores. Another option would be to maintain a certain alkali level by immersing the test core in an alkaline solution that would mimic the actual pore solution concentration in the core. The above options are currently being evaluated.

Finally, it appears that the expansion test in cores can provide useful information for the purpose expected. However, research is still needed to try to overcome some of the issues listed above, including alkali leaching of test specimens, and establish better correlations between the data generated under well-controlled laboratory conditions and field conditions (different climatic conditions).

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Table 1 : Residual expansion test results according to the method suggested in this study – compilation of expansion rates of concrete blocks in the field and from cores, and comparison with rates obtained in accordance with the method proposed by Bérubé et al. (2004).

Aggregate	Block expansion		Mean residual expansion measured on cores									
	Level at the time of coring	Rate at the time of coring (%/year)	Exp T_0 (This study) (%)	Exp T_0 (Bérubé et al. (2004)) (%)	Max exp. Used for calculation of rate (this study) (%)	Max exp. Used for calculation of rate (Bérubé et al. (2004)) (%)	Period (this study) (days)	Period (Bérubé et al. (2004)) (days)	Rate (this study) (%/year)	Rate (Bérubé et al. (2004)) (%/year)	Total value (this study) (%)[1]	Total value (Bérubé et al. (2004)) (%)[1]
Jobe	28 days		0.050 (15)	0.229 (112)	0.263 (210)	0.263 (210)	*195*	*98*	*0.40*	*0.13*	*> 0.213*[2]	*> 0.034*
	0.04%	0.31	0.045 (15)	0.107 (44)	0.193 (168)	0.193 (168)	153	124	0.35	0.25	0.148	0.086
	0.10%	2.70	0.052 (15)	0.114 (70)	0.164 (168)	0.164 (168)	153	98	0.28	0.19	0.112	0.050
	0.20%	1.52	0.027 (15)	0.094 (70)	0.155 (168)	0.155 (168)	153	98	0.31	0.23	0.128	0.061
	0.28%	1.90	0 (15)	0.064 (70)	0.112 (168)	0.112 (168)	153	98	0.27	0.18	0.112	0.048
	0.41%	1.25[3]	-0.004 (15)	0.003 (70)	0.024 (168)	0.024 (168)	153	98	0.07	0.08	0.028	0.021
Kingston	0.05%	1.44	0.086 (7)	0.261 (43)	0.327 (70)	0.392 (419)	*63*	*349*	1.40	*0.14*	*> 0.306*	*> 0.131*
	0.10%	0.73	0.134 (7)	0.329 (43)	0.377 (70)	0.446 (419)	*63*	*349*	1.41	*0.12*	*> 0.312*	*> 0.117*
	0.20%	0.53	0.129 (7)	0.342 (43)	0.396 (70)	0.471 (419)	*63*	*349*	1.55	*0.14*	*> 0.342*	*> 0.129*
	0.36%	0.86[3]	0.069 (7)	0.332 (43)	0.383 (70)	0.478 (308)	*63*	*238*	1.82	*0.22*	*> 0.409*	*> 0.146*
New Mexico	28 days		0.017 (15)	0.059 (70)	0.077 (175)	0.077 (175)	*160*	*105*	*0.14*	*0.06*	*> 0.060*[2]	*> 0.018*
	0.04%	0.50	0.000 (15)	0.010 (44)	0.041 (168)	0.041 (168)	153	124	0.10	0.09	0.041	0.031
	0.10%	0.43	0.007 (15)	0.009 (28)	0.037 (168)	0.037 (168)	153	140	0.11	0.07	0.030	0.028
	0.19%	---	--	---	--	--	--	---	--	---	--	---
Mass	28 days		0.006 (14)	0.024 (42)	0.152 (211)	0.152 (211)	*197*	*169*	*0.27*	*0.28*	*> 0.146*[2]	*> 0.128*
	0.05%	0.29	0.030 (14)	0.055 (56)	0.094 (168)	0.094 (168)	154	112	0.15	0.13	0.065	0.039
	0.09%	0.10	0.030 (14)	0.057 (42)	0.080 (140)	0.080 (140)	126	98	0.15	0.09	0.051	0.023
	0.20%	0.33[3]	0.026 (14)	0.047 (42)	0.070 (211)	0.070 (211)	*197*	*169*	*0.08*	*0.05*	*> 0.044*[2]	*> 0.023*

1 Value obtained by calculating the difference between the maximum mean expansion and the length measured after a certain period of time after the beginning of the test considered as hydric reequilibration (not related to ASR).

2 Tests still running, i.e. main phase of expansion not finished yet.

3 Rate obtained with the measure before the final measure and the final measure on the block before coring.

Table 2 : Mass gain data at different ages for core samples of the reactive aggregates selected in this study.

Aggregate	Expansion level	Mass gain (7 days)	% of total mass gain	Mass gain (14 days)	% of total mass gain	Mass gain (175* or 210 days)	% of total mass gain
Jobe	J2, 0.20%	0.49	51	0.56	58	0.91	94
	J4, 0.04%	0.59	60	0.68	69	0.95	97
Kingston	K3, 0.36%	0.58	32	1.23	68	1.74	97
	K2, 0.10%	---	---	1.24	81	1.50	98
Placitas	P28, 28 days	0.12	32	0.16	42	0.38*	100
	P3, 0.10%	0.34	53	0.35	55	0.61	95
Mass	M28, 28 days	0.52	49	0.61	58	1.06	100
	M, 0.20%	0.54	44	0.80	66	1.22	100

Table 3 : Multiplication factors to apply to the calculated expansion rates (%/year) on cores in laboratory to attain/estimate the field expansion rate (%/ year) measured on the exposure blocks.

Aggregate	Block's expansion reached at the time of coring	Block Rate at the time of coring (%/year)	Core Rate (this study) (%/year)	Ratio block/core	Multiplication factors to apply to the laboratory rate calculations (based on core expansions)
Jobe	0.04%	0.31	0.35	0.9	5 to 10 (most of the time)
	0.10%	2.7	0.28	10	
	0.20%	1.52	0.31	4.9	
	0.28%	1.9	0.27	7.0	
	0.41%	1.25	0.07	17.9	
New Mexico	0.04%	0.5	0.1	5	4 to 5
	0.10%	0.43	0.11	3.9	
Mass	0.05%	0.29	0.15	1.9	2 to 4
	0.09%	0.1	0.15	0.7	
	0.20%	0.33	0.08	4.1	

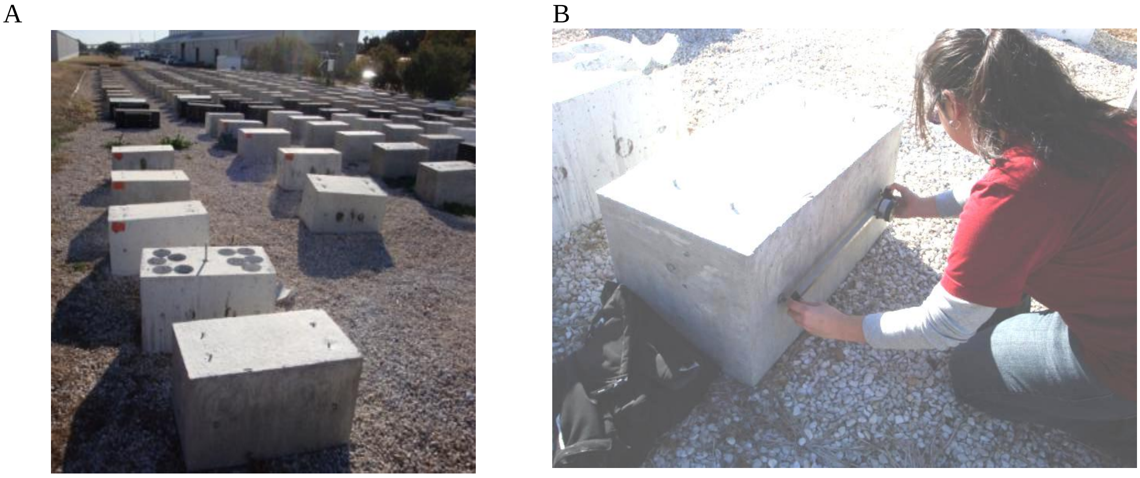

Figure 1: A. Exposure blocks on the outdoor exposure site at the University of Texas at Austin, USA. B. Expansion measurements of the exposure blocks.

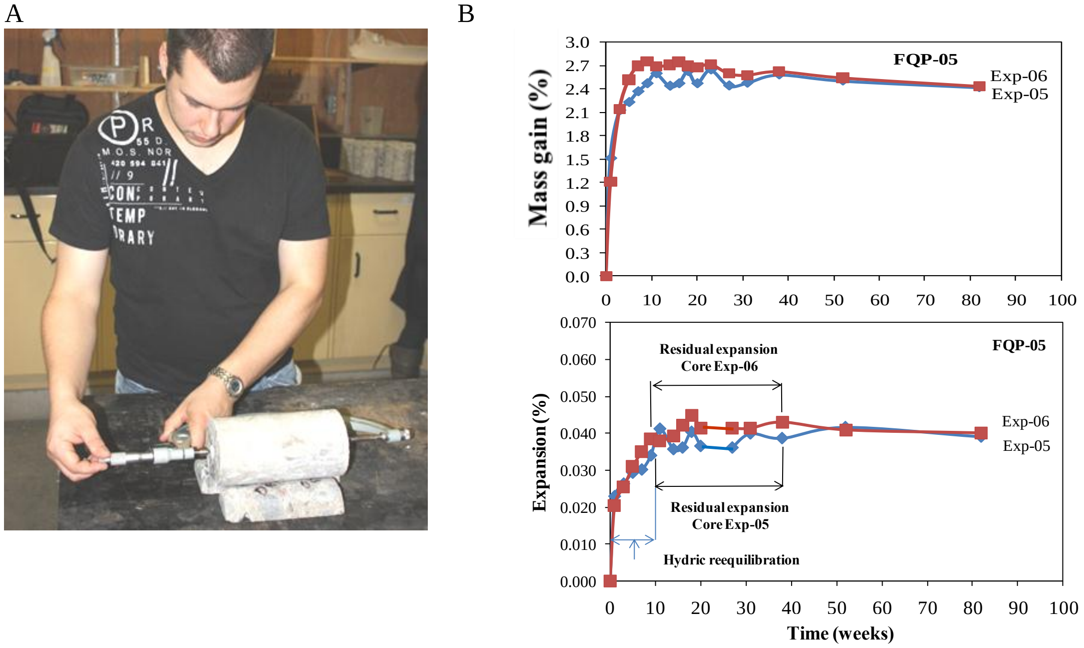

Figure 2: A. Residual expansion measurements (A) on a core sample and data analysis (B)

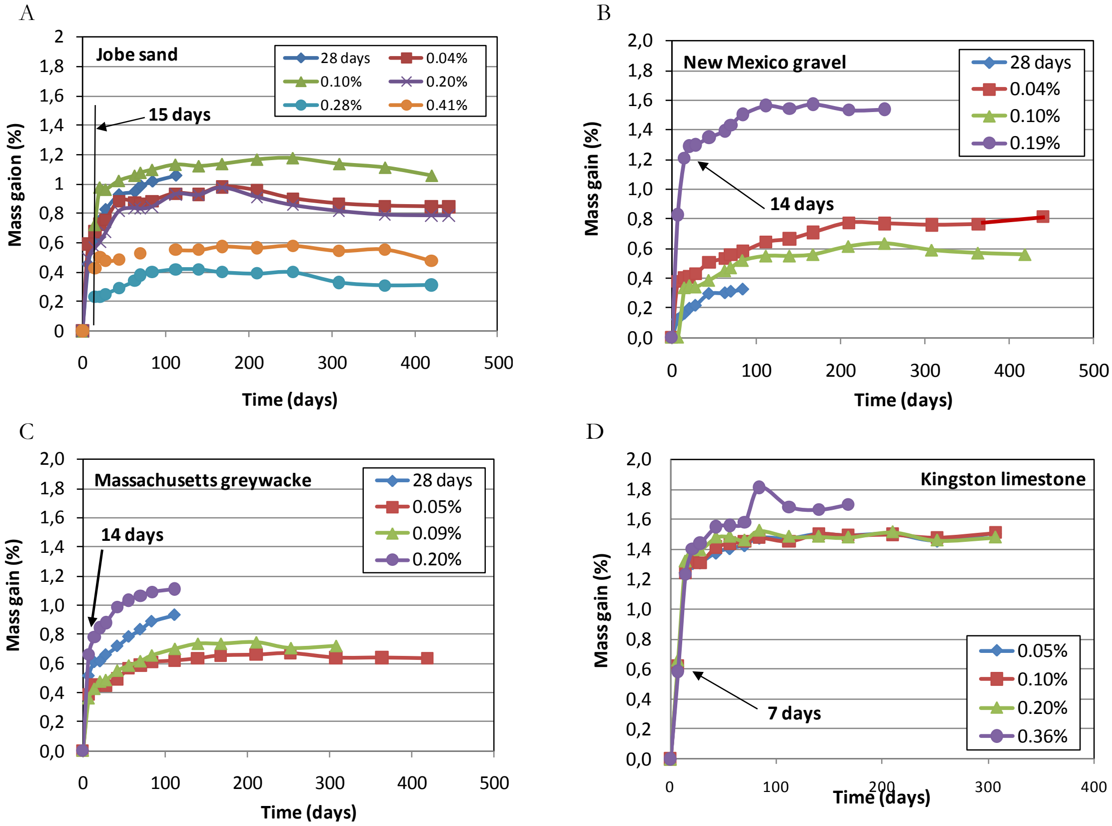

Figure 3: Mass gain curves for cores extracted from exposure blocks of various expansion levels and incorporating the various aggregates selected for this study. A. Jobe sand. B. New Mexico gravel (Placitas). C. Massachusetts greywacke. D. Kingston limestone.

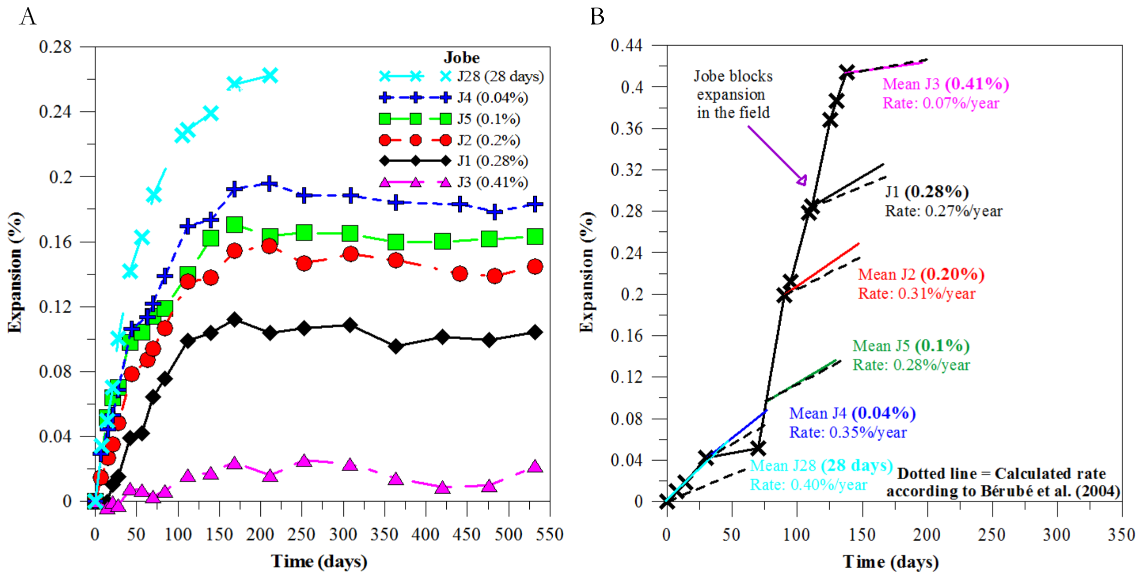

Figure 4: Jobe reactive sand. A. Expansion (%) vs time (days) for residual expansion test conducted on cores extracted from Jobe blocks at selected expansion levels (28 days to 0.41%). B. Comparison between the expansive behaviour (expansion rates) of blocks exposed outdoors and concrete cores subjected to accelerated testing in the laboratory.

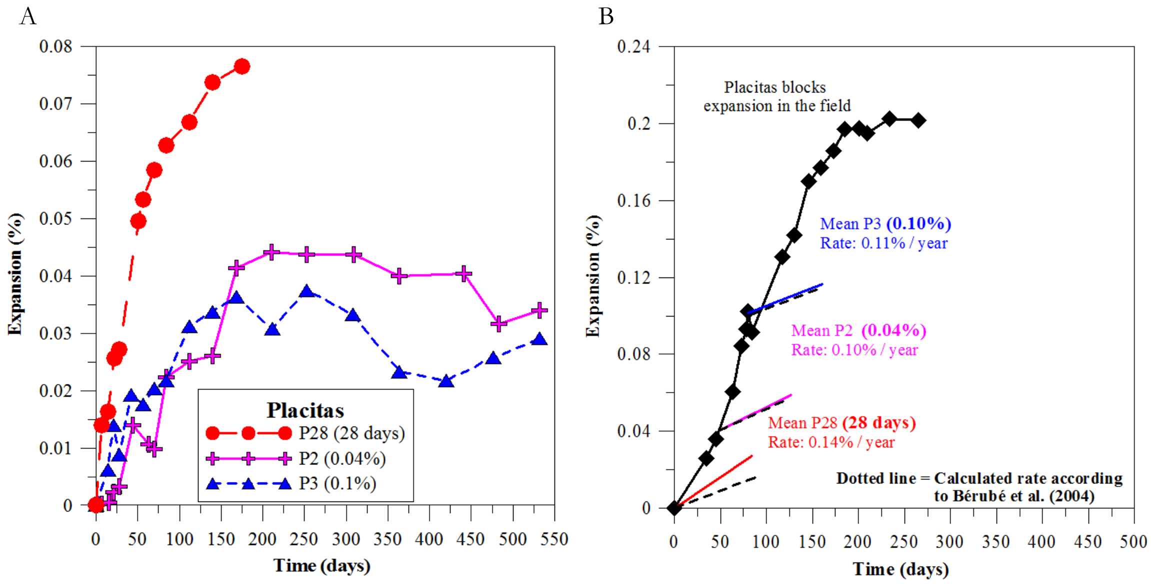

Figure 5: New Mexico gravel. A. Expansion (%) vs time (days) for residual expansion test conducted on cores extracted from Placitas blocks at selected expansion levels (28 days to 0.10%). B. Comparison between the expansive behaviour (expansion rates) of blocks exposed outdoors and concrete cores subjected to accelerated testing in the laboratory.

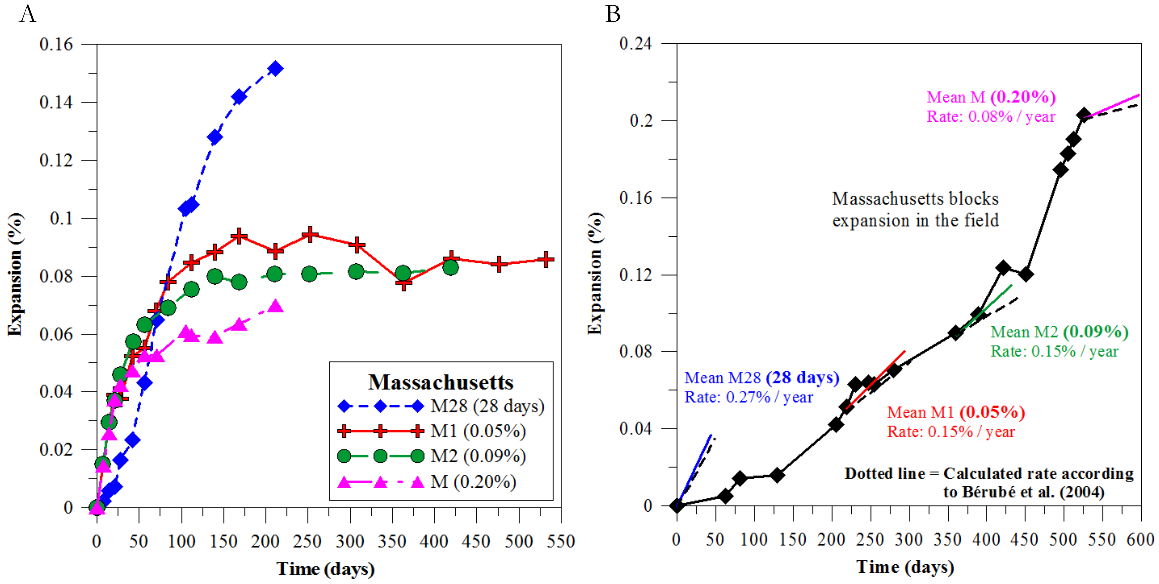

Figure 6 : Massachusetts greywacke. A. Expansion (%) vs time (days) for residual expansion test conducted on cores extracted from Massachusetts blocks at selected expansion levels (28 days to 0.20%). B. Comparison between the expansive behaviour (expansion rates) of blocks exposed outdoors and concrete cores subjected to accelerated testing in the laboratory.

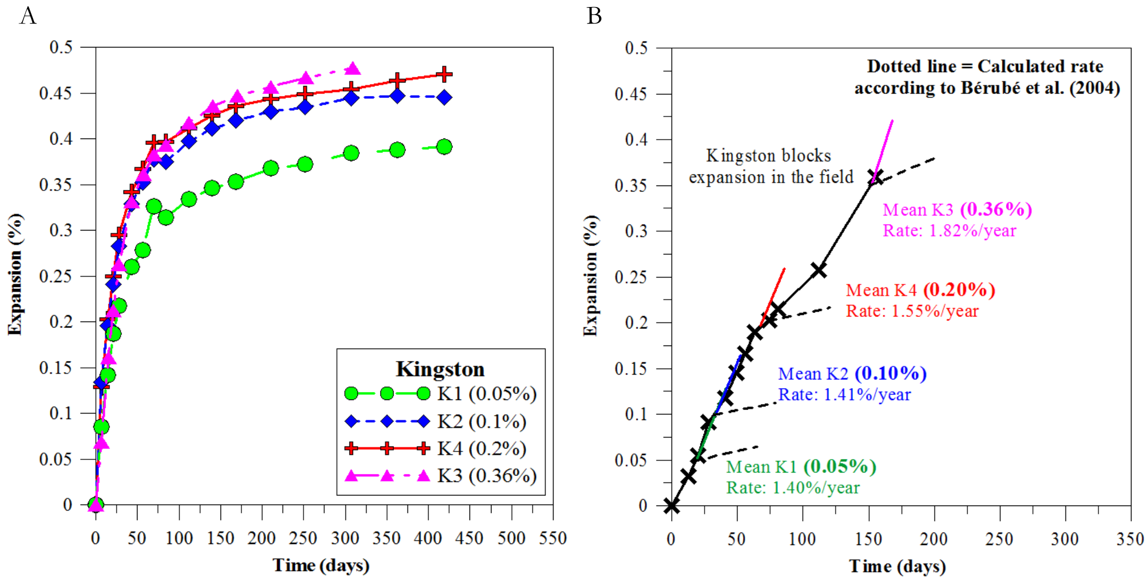

Figure 7 : Kingston limestone. A. Expansion (%) vs time (days) for residual expansion test conducted on cores extracted from Kingston blocks at selected expansion levels (0.05% to 0.36%). B. Comparison between the expansive behaviour (expansion rates) of blocks exposed outdoors and concrete cores subjected to accelerated testing in the laboratory.