

SEVEN YEARS OF FIELD SITE TESTS TO ASSESS THE RELIABILITY OF DIFFERENT LABORATORY TEST METHODS FOR EVALUATING THE ALKALI-REACTIVITY POTENTIAL OF AGGREGATES

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Abstract

Field site tests were carried out to assess the reliability of the tests developed by RILEM and some regional tests to evaluate the alkali-reactivity potential of aggregates. 100 concrete cubes made with 13 different European aggregate combinations were stored on eight different European field sites from Norway to Spain. After about 7 years of outdoor exposure all concrete samples containing aggregates that were supposed to react in normal time scales of 5 to 20 years based on the reported damaging reaction in structures showed cracks and significant expansions at all field sites. The reactivity potential of these aggregate combinations was successfully identified with all test methods. Some aggregate combinations that were classified as “slowly” reactive showed first signs of a damaging alkali silica reaction (ASR) on at least one field site.

Keywords: Alkali-silica reaction, Test-methods, Outdoor exposure site, aggregate assessment

1 INTRODUCTION

World wide many test methods have been developed to evaluate the potential alkali-reactivity of aggregates and to mitigate deteriorations of concrete structures caused by damaging alkali-silica reaction (ASR). Test methods have to be accurate and must reliably predict the alkali-reactivity potential of aggregate combinations under those real-life conditions that concrete structures are exposed to. This paper presents the results of field site tests after 7 years of outdoor exposure to evaluate the tests developed by RILEM (AAR-1, -2, -3, -4) and some regional tests (Danish mortar bar test, Danish Chatterji method, German concrete method and Norwegian concrete prism method) for their suitability to assess the potential alkali-reactivity of aggregates. The field site tests were part of the EU PARTNER Project (2002-2006), which had the overall objective of establishing a unified test procedure for evaluating the potential alkali-reactivity of aggregates across the different European economic and geological regions. The final results and recommendations of the EU PARTNER Project are summarised in [1, 2]. All test methods are shortly described in Table 1.

The final results of the PARTNER Project showed that all the RILEM test methods and all the regional test methods were successful in identifying “normally” reactive (timescales of reaction 5 to 20 years) and non-reactive aggregates. All the “normally” reactive aggregates developed high expansions and cracks in the outdoor exposed concretes within 4 years on at least one field site [2, 12]. But whether these test methods are suitable for identifying “slowly” reactive aggregates that react after 15 to 20 years must be verified by comparison of the laboratory test results [1, 2] with the performance of the field exposed concretes cubes, which are stored under conditions that are closer to those experienced by actual structures.

The influence of different climatic conditions representative for Europe is covered by 8 different field sites from Norway to Spain (Figure 1). To study the influence of alkali supply by de-icing salts, specimens

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were stored in southwest of Sweden at two different field sites. In laboratory tests, it has previously been found that samples containing reactive aggregates showed higher degrees of reaction if exposed to salt solutions instead of water [13-15].

Furthermore concrete that was partly immersed in water was investigated to determine if it would exhibit faster and higher degrees of deterioration than concrete that is only exposed to ambient rainfall.

2 MATERIALS AND METHODS

2.1 General

To evaluate the reliability of different laboratory test methods, concrete cubes were produced from the same concrete batch as the prisms for the RILEM tests AAR-3 [7] and AAR-4 [8]. The concrete cubes with 300 mm lateral length were stored at different outdoor exposure sites. The expansion and the maximum crack width were determined periodically at approximately the same temperature.

2.2 Materials and mixture proportions

Materials

Thirteen aggregate combinations were selected with the purpose of covering most types of reactive aggregates throughout Europe and with respect to mineralogical properties and alkali-reactivity (Table 2). In some cases the coarse fraction was tested in combination with non-reactive sand (N3 from Norway) or a fine fraction was tested with a non-reactive coarse aggregate (F2 from France) or the fine and the coarse fractions were tested together. Additionally, non-reactive reference aggregates (F2) were tested. A brief petrographic description and details about the reported reactivity in concrete structures of these aggregates are given in [2].

The RILEM standard cement CEM I 42,5 R provided by NORCEM was used for preparing the concrete. The total alkali content of the cement was 1.26 wt% sodium equivalent. In case of inappropriate workability of the concrete (slump < 20 mm) a superplasticizer was added. No air entraining agent was added to the concrete mix.

Concrete mixing and casting

Concrete was made with 440 kg/m³ cement and the water to cement ratio was 0.50. The air content was approximately 2 vol%. In accordance with the RILEM test method AAR-3 [7] and AAR-4 [8] the aggregate combination consisted of one of the following:

- the fine and coarse test aggregates (C + F);
- the fine test aggregate combined with non-reactive coarse aggregate (F + NRC);
- the coarse test aggregate combined with non-reactive fine aggregate (C + NRF).

The aggregate fractions were combined in proportions of 30 wt% fines (0 to 4 mm) and 70 wt% coarse aggregates: 30 wt% 4 to 10 mm and 40 wt% 10 to 20 mm.

Two concrete cubes with 300 mm lateral length were produced for each field site and each aggregate combination. The cubes were kept for one day in the moulds, de-moulded and stored in a room at $(20 \pm 2)^\circ\text{C}$ and $\geq 95\%$ relative humidity (or were covered with moist fabric) for 6 days before being transported to the different field sites. All the cubes representing one concrete mix (i.e. one aggregate type) were cast at one laboratory (generally in the country of origin of the aggregate) and transported to all the other laboratories (field test sites).

2.3 Field site testing

At the different field sites, each institute that participated in this research glued two pairs of reference studs into the top surface and into the two adjacent side faces, before the cubes were exposed outdoors. All

cubes were stored in the same direction in relation to the four cardinal points to minimize deviations between the labs resulting from different exposure to direct solar radiation.

During exposure, one cube was stored with its base in a tray filled with water and the other was exposed only to ambient rainfall (Figure 2). The tray was filled with water to simulate a permanently wet concrete, so that the bottom of the first cube was immersed 50 to 60 mm in water during the whole testing time. The reference points at the bottom of the first cube were always above water level enabling length change measurements.

The concrete cubes were stored on eight different field sites that were selected to cover all climates in Europe. The mean monthly temperature and precipitations are given for each field site in Figure 3. In Sweden some specimens were stored on two field sites to study the influence of alkali supply by de-icing salts: behind the guardrail alongside the highway 40 between Borås and Gothenburg (with external alkali supply by de-icing salts) and in a nearby forest. Based on data for the years 2000 to 2003 taken from [20] it is estimated that about 1.2 kg/m² of sodium chloride was spread on the highway annually. The cubes were stored at the same place alongside the highway as the samples in [20].

The dimensions of the cubes at the top surface and two adjacent side faces as well as the crack width were determined periodically (first 2½ years every three months, afterwards every half year). Some laboratories have only measured once a year. The measurements were done at the field site at temperatures around 15°C.

3 RESULTS

The results of the laboratory tests and the field sites test as well the reported reactivity in structures are summarized in Tables 3 and 4, where the aggregates are grouped as done in [2] into three categories according to their reported field behaviour and the current field site results:

- "normally" reactive aggregates that react in timescales of 5 to 20 years based on field experience,
- "slowly" reactive aggregates (+15-20 years) based on field experience and
- non-reactive aggregates based on field experience.

The results of the laboratory tests were excerpted from [2]. Previous results showed that there were no obvious differences between the specimens exposed only to ambient rainfall and those stored partly immersed in water [2]. Therefore only the expansions for the cubes exposed to ambient rainfall are presented in Figure 4 to 6. Due to problems with the determination of dimension changes of the cubes or the use of the provided result files of some laboratories, the expansion measurements were re-started approximately one year after casting. Expansions above 0.04% are regarded as an indication that a damaging ASR is going to take place. This level was also applied for outdoor exposed concrete block to compare the expansions in different climates [16]. The maximum crack width is not presented in this paper.

“Normally” reactive aggregate combinations

After 7 years of outdoor exposure all concrete cubes with “normally” reactive aggregate combinations [**B1**(C+NRF), **B1**(C+F), **UK1**(C+F), **G1**(C+NRF), **N1**(C+NRF) and **D2**(F+NRC)] showed high expansion above 0.04% at all field sites (Figure 5). Overall, expansions developed faster in hot (Valencia, Milan) and medium (Düsseldorf, Watford) climates than in cold climates (Borås, Brevik and Trondheim) with the exception of **B1**(C+F) in Düsseldorf and Valencia as well as **UK1**(C+F) in Valencia. The comparison of **B1**(C+F) and **B1**(C+NRF) suggests that the damaging reaction of the coarse fraction is influenced by the fine fraction. The coarse fraction of the aggregate **B1** caused similar expansions on all field sites if combined with a non-reactive fine fraction [**B1**(C+NRF)], but in combination with its reactive fine fraction a lower expansion rate occurred after 4 years in Valencia. Very fine particles of reactive aggregates have the capability

to react pozzolanic and its reactivity increases with increasing temperature [17]. It can be assumed that warmer climates increase the reaction of parts of the reactive fine aggregate, reduce thereby the hydroxyl ion concentration in the pore solution and the degree of reaction of the coarse fraction. Thin section analysis at the end of the field site tests may confirm this.

The aggregates responded very differently to hot and cold. This was also found in other field site tests with outdoor exposure sites in the USA and in Canada [16]. In case of D2(F+NRC), a reactive fine aggregate (sea gravel semi-dense flint), the difference between hot (Valencia) and cold (Trondheim) climate was the greatest. An expansion of 0.04% was reached in Valencia approximately after 2 years and in Trondheim not before 4½ years. Whereas in case of B1(C+F) all expansions exceeded 0.04% between 2 to 3 years in all climates. Thus, it is not possible to derive a general climate-based factor by which the expansion is accelerated based on the data presented herein.

“Slowly” reactive aggregate combinations

Concrete cubes with some “slowly” reactive aggregate combinations like N4(C+F), S1(C+F) and P1(C+NRF) started to expand slowly after 7 years of outdoor exposure in hot climates like in Valencia and Milan (Figure 6). Even N2(C+NRF) and F1(C+NRF) showed first expansions above 0.04% in Brevik and Watford. S1(C+F) is also starting to crack with a current maximum crack width of 0.4 mm in Valencia and 0.1 mm in Düsseldorf (no figure). Ongoing measurements over the next years will give confidence in these trends. The two concrete cubes with IT2(C+F) did not expand and did not show any cracks so far.

Non-reactive aggregate combination

The concrete cubes with F2(C+F) are not exhibiting any sign of expansion or cracking yet. Furthermore current and continuing exposure will confirm or further deny these results (Figure 4).

4 DISCUSSION

The results summarised in Table 3 illustrate that all laboratory test methods were successful in identifying all “normally” reactive aggregate combinations apart from D2(F+NRC). In this case the AAR-3 method did not identify its reactivity potential whereas AAR-1, AAR-2, two of three AAR-4-tests, TI-B51 and the Danish Chatterji method did [2].

In the case of “slowly” reactive aggregate combinations the results are not as conclusive as for the “normally” reactive aggregate combinations. The petrographic method AAR-1 was very effective in identifying the potential alkali-reactivity of these “slowly” reactive aggregate combinations, but the classification of the aggregates according to their potential alkali-reactivity varied between laboratories in precision trials [2]. Assuming the expansion-trends in the field site tests are ongoing as observed in Figure 5, the results confirm that the RILEM AAR-2 and AAR-4 method are the most reliable test methods to identify “slowly” reactive aggregate combinations like S1(C+F) and N4(C+F). The AAR-3 failed in 4 of 6 cases to detect the potential reactivity. Similar experience was gained in [18] with slowly reactive Australian aggregates. Tests with the RILEM AAR-4 methods reliably predicted the potential alkali-reactivity of these aggregates, that caused damage in concrete structures. Concrete prism tests at 38°C (similar to AAR-3) did not identify their potential reactivity and the accelerated mortar bar tests were on the borderline [17].

Nonetheless, there are concerns about the accuracy of the AAR-4-method in predicting the reactivity potential since the expansions were significantly reduced in concrete prism tests similar to AAR-4 compared to tests similar to AAR-3 [19]. Besides, the selection of non-reactive sands had a significant impact on the concrete expansion if reactive coarse aggregates were tested. The different sands were all tested non-reactive with AAR-2.

Apart from the petrographic method (AAR-1) and the Danish Chatterji method, all methods did classify the F1(C+NRF) (gravel with flint) as non-reactive, although F1(C+NRF) showed first expansions in two field sites. No damage with this aggregate is reported in structures, but it is known to show pessimum behaviour. To identify the reactivity potential additional methods should be used. Tests with different cement to aggregate ratios like the French chemical-, autoclave- and microbar-test according to AFNOR XP P 18-594 could be applied. Alternatively the aggregate could be tested in mortar bar or concrete prism tests in different proportions with a non-reactive aggregate. The amount of reactive flint could also be calculated with the mean flint density according to the German Alkali-Guidelines [9].

In case of the non-reactive aggregate combination F2(C+F), the laboratory test results of all methods were in line with the performance at the field site and the reported reactivity.

The comparison of test results from the two field sites in Sweden indicate that there is no significant difference in the performance of the concrete cubes stored in a nearby forest (without alkali supply) and alongside the highway (with alkali supply) so far. In some cases results are not given until the 7th year because studs had fallen off. Thus, measurements were not possible to be taken for some aggregate combinations.

5 CONCLUSIONS

Field site tests were carried out to assess the reliability of the different methods to evaluate the alkali-reactivity potential of aggregates. After about 7 years of outdoor exposure, the main conclusions from this research are as follows:

- “Normally” reactive aggregate combinations (timescale of reaction 5 to 20 years based on field experience) caused significant expansion of concrete cubes (expansion > 0.04%) at all field sites from Norway to Spain within 7 years of outdoor exposure.
- Five of six “slowly” reactive aggregate combinations (timescale of reaction > 15 to 20 years based on field experience) showed first indications of damaging ASR after seven years on at least one field site - mainly in hot climate.
- Alkali-reactive aggregates respond very differently to hot and cold climates. Thus, the effect of climate conditions on the progress of the alkali-silica reaction differs from aggregate to aggregate.
- The field site tests confirm that all laboratory tests correctly identified “normally” reactive and non-reactive aggregate combinations. However, the RILEM test methods AAR-2 and AAR-4 gave the most reliable results in case of “slowly” reactive aggregate combinations to predict the damaging reaction.
- No significant differences in performance of the concrete cubes were observed in field site tests with storage alongside a highway (with alkali supply) and in a nearby forest (without alkali supply) so far.

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Test method	Brief outline of method
RILEM AAR-1 Petrographic method [3]	The reactivity of the aggregate is classified on the basis of its petrographic composition. Depending on the nature of the aggregate this can either be by hand separation, crushing and point counting under a microscope or by microscopic examination in thin section.
RILEM AAR-2 Accelerated mortar bar method [4]	Mortar bars made with the aggregate and a reference high alkali cement are stored in 1M NaOH at 80°C and their expansion monitored over a 14 day period.
TI-B51 - The Danish mortar bar test [5]	Mortar bars made with the aggregate are stored in saturated NaCl solution at 50°C and their expansion is monitored for 52 weeks.
The Danish Chatterji method [6]	The degree of reaction between silica in the aggregate and KCl is determined by measuring the alkalinity after 24 hours reaction compared to a non-reactive standard.
RILEM AAR-3 Concrete prism method [7]	Accelerated expansion test for 12 months. Wrapped concrete prisms, $(75\pm 5)\times(75\pm 5)\times(250\pm 50)$ mm ³ , made with the aggregate and a reference high alkali cement (1.25% ± 0.05% sodium oxide equivalent) are stored in individual containers within a constant temperature room at 38°C and measured at 20°C.
RILEM AAR-4 Accelerated concrete prism method [8]	Accelerated expansion test for 20 weeks. Concrete prisms, $(75\pm 5)\times(75\pm 5)\times(250\pm 50)$ mm ³ , made with the aggregate and a reference high alkali cement (1.25% ± 0.05% sodium oxide equivalent) are stored in individual containers within a reactor at 60°C and measured at 20°C.
RILEM AAR-4 Alt. Accelerated concrete prism method [8]	Accelerated expansion test for 20 weeks. Wrapped concrete prisms, $(75\pm 5)\times(75\pm 5)\times(250\pm 50)$ mm ³ , made with the aggregate and a reference high alkali cement (1.25% ± 0.05% sodium oxide equivalent) are stored in individual containers within a constant temperature room at 60°C and measured at 20°C.
German concrete method [9]	Test duration of 9 months. Concrete prisms (100x100x450 mm ³) and one cube (300mm ³) are stored in a fog chamber at 40°C with measurements taken immediately with no cooling down period. The expansion of concrete prisms and the maximum crack width on the cube are determined.
Norwegian concrete prism method [10]	Accelerated expansion test for 12 months. Large concrete prisms (100x100x450 mm ³) made with the aggregate and a reference high alkali cement are stored in individual containers within a constant temperature room at 38°C and 100% relative humidity and measured at 20°C.
Field site method [1, 2, 11, 12]	300mm ³ concrete cubes stored on outdoor exposure sites. Measurements of expansions and maximum crack widths.

Sample number	Origin	Aggregate details	Combinations *
B1	Western Belgium	Silicified limestone	C + F
B1	Western Belgium	Silicified limestone	C + NRF
D2	Denmark	Sea-dredged gravel semi-dense	F + NRC
F1	France (Seine Valley)	Gravel with flint	C + NRF
F2	France	Non-reactive limestone	C + F
G1	Germany (Upper Rhine Valley)	Crushed gravel with siliceous	C + NRF
It2	Italy (Piemont region)	Gravel with quartzite and gneiss	C + F
N1	Norway (middle)	Cataclasite	C + NRF
N2	Norway (south east)	Sandstone	C + NRF
N4	Norway (south east)	Gravel with sandstone and catacl.	C + F
S1	Sweden	Gravel with porphyritic rhyolite	C + F
UK1	United Kingdom	Greywacke	C + F
P1	Portugal	Silicified limestone	C + NRF

* C = coarse aggregate; F = fine aggregate; NRC = non-reactive coarse aggregate (= F2C, see Table 3); NRF = non-reactive fine aggregate (=N3F, see Table 3)

TABLE 3: Comparison of results of test methods with behaviour in field sites and structures of “normally” reactive aggregate combinations. Excerpted from [2]									
Aggregate	Fraction/ combination	Reactivity / evaluation							
		AAR-1	AAR-2	AAR-3	AAR-4/ AAR-Alt	TI-B51/ Chatterji	German/ Norwegian	Field site test after 7 years*	Reported reactivity in structures?
“Normally” reactive aggregate combinations									
B1 - Silicified limestone	F C C+F C+NRF	R R	R		R R	R/R		R R	Yes
UK1 - Greywacke	F C C+F	R R	R		R R/R	R/R		R	Yes, normally +20 years
G1 - Crushed gravel with siliceous limestone and chert	C C+NRF	R	R		R R/R	R/-		R	Yes, 10 years if severe conditions
N1 - Cataclasite	C C+NRF	R	R		R R/R	R/R		R	Yes, 10-15 years
D2 - Sea gravel semi-dense flint	F C F+NRC	R R	R		NR/MR? R/MR	R/R		R	Yes, 10-15 years
“Slowly” reactive aggregate combinations									
It2 - Gravel with quartzite	F C C+F	R R	R		NR R/R	NR/-		n.r.	Yes, 50 years
N2 - Sandstone	C C+NRF	R	R		R	NR/R		-/R R**	Yes, 15-20 years
N4 - Gravel with sandstone and cataclastic rocks	F C C+F	R R	R		MR R/-	R/R		MR/MR R**	Yes, 20-25 years
F1 - Gravel with flint	C C+NRF	R	NR		NR NR/NR	NR/R		NR/- R**	No, but known pessimism effect
S1 - Gravel with metarhyolite and greywacke	F C C+F	R R	R		NR MR/-	R/R		NR/MR R**	Yes, but source variable in composition
P1 - Silicified limestone	C C+NRF	R	NR		NR NR-MR/ MR	NR/-		R**	Yes, but source and information uncertain
Non-reactive aggregate combinations									
N3 - Granitic sand	F C C+F	NR NR	NR		NR NR/NR	NR/NR		NR/NR -	No
F2 - Non-reactive limestone	F C C+F	NR NR	NR		NR NR/NR			NR/NR n.r.	No
<p>F = fine aggregate; C = coarse aggregate NRF = non-reactive fine aggregate (=N3F); NRC = non-reactive coarse aggregate (=F2C) R = reactive (according to the critical limits in the different testing methods) NR = non-reactive (according to the critical limits in the different testing methods) MR = marginally reactive (i.e. expansions just above the critical limits in the different testing methods) n.r. = no rating yet possible R** = first indications of a reaction on at least one field site * = the evaluation of the preliminary results from the field sites is based on measurements of crack widths after about 7 years of exposure and of expansions during the last 7 years (the expansion measurements were re-started in 2005 due to problems with the zero measurements at some field sites).</p>									



FIGURE 1: Location of outdoor exposure sites with two field sites near Borås. Excerpted from [2]

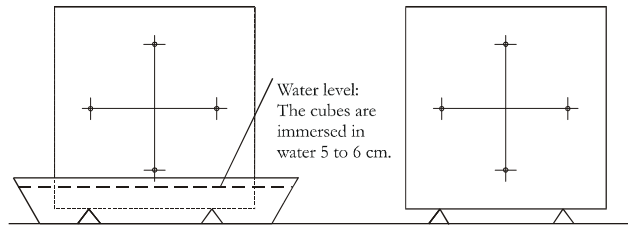


FIGURE 2: Storage of cubes at the field site. Excerpted from [2]

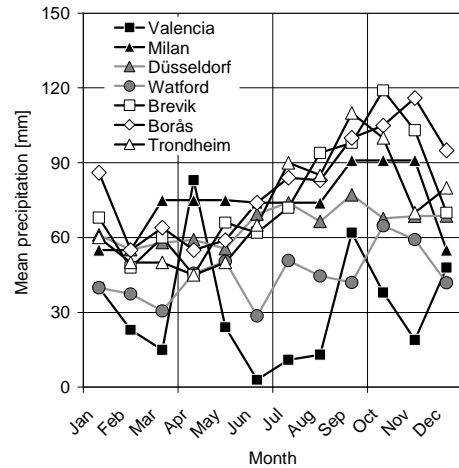
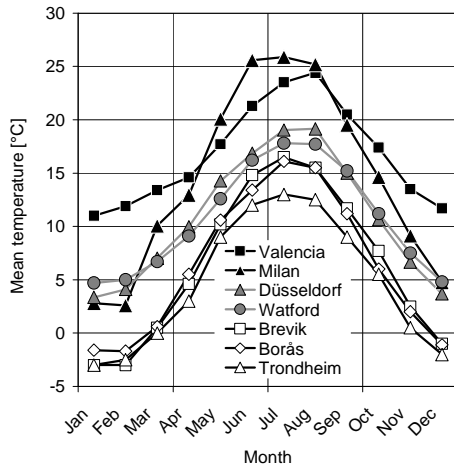


FIGURE 3: Mean temperature and precipitation at different field sites. Excerpted from [2]

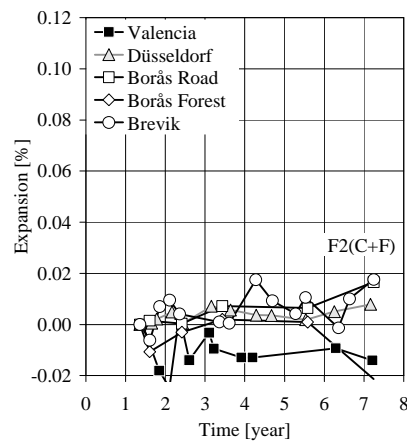


FIGURE 4: Mean expansion of concrete cubes with a non-reactive aggregate combination stored in different European field sites, only exposed to ambient rainfall

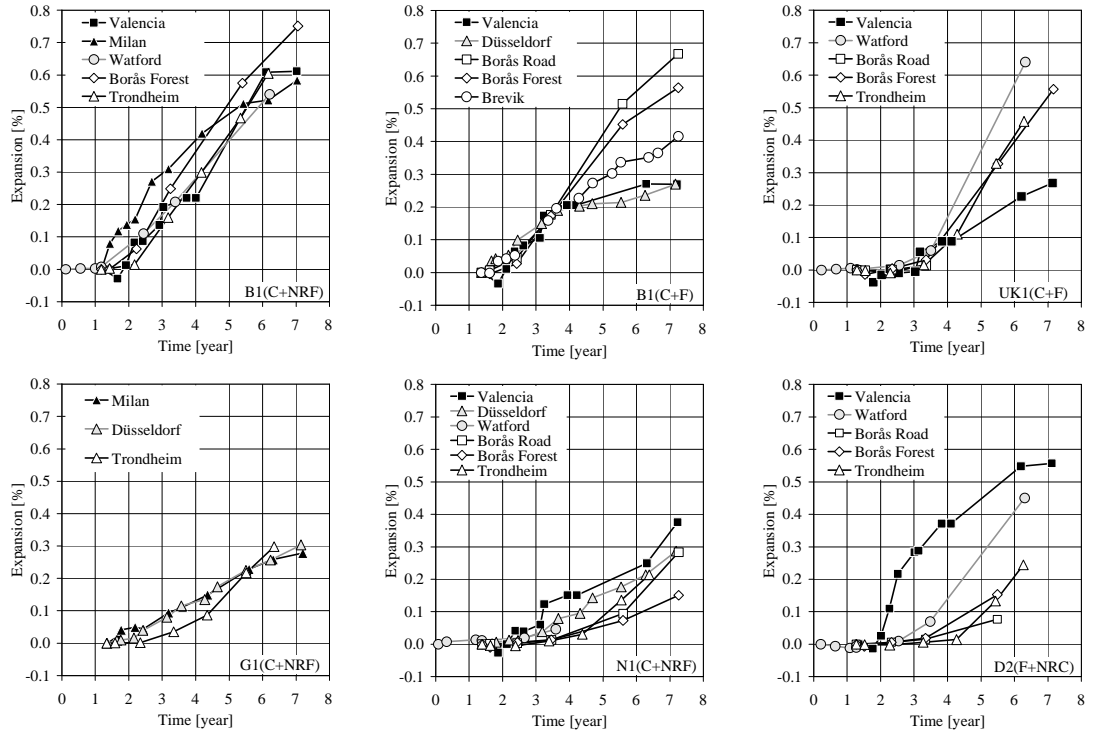


FIGURE 5: Mean expansion of concrete cubes with different “normally” reactive aggregate combinations stored in different European field sites, only exposed to ambient rainfall

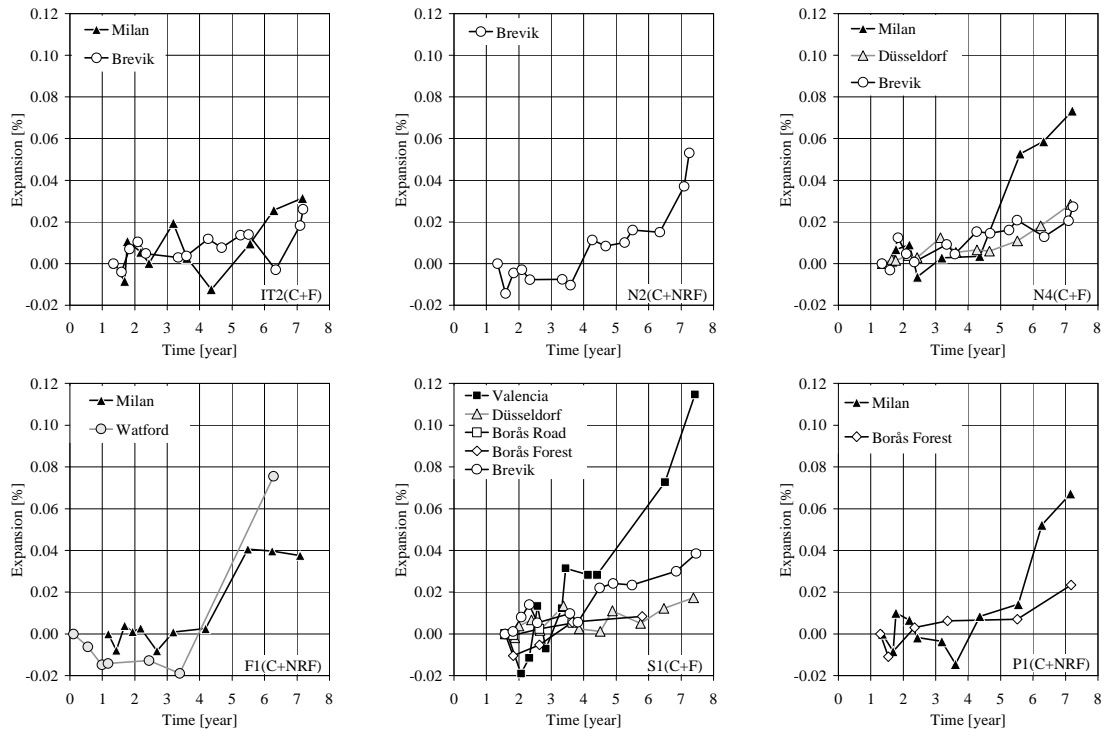


FIGURE 6: Mean expansion of concrete cubes with different “slowly” reactive aggregate combinations stored in different European field sites, only exposed to ambient rainfall