

FIELD SITE TESTS ESTABLISHED IN THE PARTNER PROJECT FOR EVALUATING THE CORRELATION BETWEEN LABORATORY TESTS AND FIELD PERFORMANCE

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Abstract

This report describes the results of field site tests established in the PARTNER project to evaluate test methods developed by RILEM and two regional test methods to assess the alkali reactivity of aggregates. The results provide a correlation between the behaviour of aggregates or aggregate combinations in tests with RILEM test methods and under real climatic conditions. In total 100 cubes were produced for 50 tests at 8 different field sites. Concretes with 13 different European aggregate combinations were partly stored in various climate zones representative for Europe in order to take into account the influence of different environmental conditions.

After approximately 3½ years of exposure all concrete samples containing aggregates that react in normal timescales of 5 to 20 years in structures showed significant signs of a deleterious alkali silica reaction (ASR). These aggregates were all identified as reactive in laboratory tests.

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

1 INTRODUCTION

This paper describes the current state of results of field site tests which were carried out under Work Package 3.5 [1] of PARTNER (www.partner.eu.com), a project funded by the European Community. In PARTNER the tests developed by RILEM committees TC106 and TC191-ARP ([2], [3], [4], [5]) and some regional tests (amongst others the German fog chamber- and Norwegian methods) ([6], [7]) were evaluated for their suitability for use with the wide variety of aggregates and geological types found across Europe.

The field site tests were included to provide a means of calibrating the accelerated tests against behaviour in conditions closer to those experienced by actual structures for evaluating the reliability of different laboratory test methods to assess the alkali reactivity of aggregates. The degree of reactivity respectively the timescale in which deterioration appears with a specific aggregate combination is considered. Different climatic conditions representative for Europe are covered in order to take into account the influence of different environmental conditions. Furthermore it is unclear if concrete that is partly immersed in water would exhibit faster and higher degrees of deterioration due to alkali silica reaction (ASR) than a concrete that is only exposed to ambient rainfall.

In laboratory tests it was found that samples showed higher expansion if exposed to de-icing salts instead of water. Therefore de-icing salts are believed to promote a deleterious ASR in concrete with reactive aggregates ([8], [9], [10]). To study the additional influence of alkali supply under severe climatic conditions specimens were stored alongside a highway and in a nearby forest in Sweden.

2 MATERIALS AND METHODS

2.1 General

To evaluate the suitability of accelerated tests concrete samples for the RILEM tests (AAR-3 [4] and AAR-4 [5]) and for the field site tests were produced from the same concrete batch and were tested parallel to each other. 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.

2.2 Materials

Aggregates

Thirteen aggregate combinations have been selected with respect to mineralogical properties and alkali-reactivity (table 1). The aggregates were selected with the purpose of covering most types of reactive aggregates throughout Europe. In some cases the coarse fraction was tested in combination

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with non-reactive sand (N3 from Norway) or a fine fraction was tested with a non-reactive coarse aggregate (F2 from France). Additionally, non-reactive reference aggregates were tested. Details of the aggregates are given in a series of technical reports published by the Norwegian research institute SINTEF [1], [11], [12], [13], [14]. These reports may be downloaded free of charge (www.partner.eu.com). The water absorption and density were determined according to EN 1097-6.

Cement

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 is 1.26 wt% sodium equivalent, the density was 3.12 g/cm³. Due to the high alkali content an addition of sodium hydroxide to the mixing water to reach the requested alkali content of (1.25 ± 0.05) wt% sodium equivalent in the cement according RILEM AAR-3 [4] and AAR-4 [5] test method was not necessary.

Admixtures

In case of inappropriate workability of the concrete (slump < 20 mm) a superplasticizer was added.

2.3 Concrete production

Concrete mixing and casting

The cement content was 440 kg/m³ to ensure sufficient alkalis (440 kg/m³ x 1.26 wt% Na₂O_{eq} = 5.54 kg/m³ Na₂O_{eq}) in the mix. The effective water to cement ratio was 0.50. The air content was approx. 2 vol%.

In accordance with the RILEM test method AAR-3 [4] and AAR-4 [5] 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 volume 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.

After the concrete production two concrete cubes with 300 mm lateral length were cast and compacted in steel moulds at (20 ± 2)°C. The concrete cubes were demoulded after (24 ± 0.5) hours and stored in a room at (20 ± 2)°C for 6 days. To avoid loss of water they were covered with moist fabric or stored at ≥ 95% relative humidity. Afterwards the cubes were put in a room at (20 ± 2)°C and at (65 ± 5)% relative humidity for 21 days.

The concrete specimens were produced in different laboratories in different countries. All cubes representing one concrete mix (i.e. one aggregate combination) were cast at one laboratory and transported to all the other laboratories/field sites.

Preparation for measurement

After 28 days two pairs of reference studs were glued on the top surface and on two adjacent side faces to measure the change of dimension. Figure 1 shows each position of the reference studs and the measuring directions.

Specimen storage

If a cube was sent to other field sites/laboratories, this was done after curing the cubes for 6 days in a room maintained at (20 ± 2)°C and ≥ 95% relative humidity. The cubes were transported on a wooden palette and covered with a plastic foil to avoid direct water contact during transport. The cubes should have arrived at the test sites 26 days after casting. At the test sites the cubes were stored in a room at (20 ± 2)°C until final preparation for measuring length changes. In general the cubes were stored at the field site 28 days after production. Due to some problems in one laboratory some cubes were stored in the laboratory up to four month after production before they were stored at the field site.

For each aggregate combination/concrete the first cube was stored with its base in a tray filled with water (wet storage) and the second cube was exposed only to ambient rainfall (dry storage) (see figure 2). The tray was filled with water to simulate a permanently wet concrete, so that the bottom of the first cube was immersed 5 to 6 cm 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.

All cubes were stored in the same direction in relation to the compass rose (see figure 3) to minimize deviations between the labs resulting from different exposure to direct solar radiation.

2.4 Field site testing

Field site selection

Eight different field sites were selected to cover all climates in Europe, where ASR has caused damage to concrete structures. Furthermore some specimens were stored alongside a highway between Borås and Gothenburg in Sweden and in a nearby forest to study the additional influence of alkali supply by de-icing salts. The field sites and a brief description of their climate according to Köppen are summarized in table 2. The mean monthly temperature and precipitations are given in figure 4.

Testing at field site

For the detection of possible deterioration due to ASR 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 measurement was done at the field site. Extreme temperatures should have been avoided. The increase in dimensions of the cubes was calculated for each period of measurement. Thereby it was differentiated between the diagonal dimensions on the surface, the horizontal dimensions and the vertical dimensions on the side faces.

3 RESULTS

In summer 2007 the samples had been exposed at the outdoor exposure sites for approximately 3 to 3½ years. The current state of the maximum expansion and the maximum crack width of the cubes is summarized for each aggregate combination/concrete and field site in table 3 for cubes that were partly immersed in water (“wet storage”) and table 4 for cubes that were exposed only to ambient rainfall (“dry storage”). After approx. one year of exposure a new “zero” measurement was necessary because some laboratories had problems with the determination of dimension changes of the cubes or the use of the provided result files. Thus the expansions are measured for approx. 2 years.

Extensive expansion $> 0.04\%$ which occurred since the new “zero” measurement in June 2005 and cracks $\geq 0.20\text{mm}$ which occurred in 3 to 3½ years of testing are highlighted in table 3 and 4 (see grey highlighted values). Exceeding of the limits is an indication that a deleterious ASR might have taken place.

The cubes of B1(C+F) and B1(C+NRF) show high expansion $> 0.04\%$ and cracks with maximum width $\geq 0.20\text{mm}$ at all field sites independent of the type of storage. B1(C+NRF) shows high expansions and big cracks independent of the climate condition from Norway to Spain (see figure 5). The aggregate compositions D2, G1, N1 and UK1 show high expansions and big cracks when stored in medium (VDZ, BRE) and hot climates (AIDICO, Cesi Ricerca). Figure 6 exemplifies this for N1 that shows high expansions only in hot (AIDICO) and medium (VDZ, BRE) environments whereas it shows no expansion in cold climates (SP, SINTEF) yet. The increase in expansion is greater in the hot climates (AIDICO) than in the middle of Europe (VDZ, BRE).

The slowly reactive aggregates IT2, N4, S1 and P1 and the non-reactive aggregates F1 and F2 did not show any noticeable expansion or cracking yet. Small cracks with a width of 0.05 mm are visible at most cubes. But N2 and D2 did show signs of reaction.

The specimens that were only exposed to ambient rainfall showed higher expansions and big cracks more often than the specimens that were partly submerged in water.

No differences are obvious between the cubes that were stored in a forest and beside a highway between Borås and Gothenburg in Sweden.

B1(C+NRF) seems to have slightly higher expansion and sometimes bigger cracks than B1(C+F) which contains reactive fines instead of non-reactive fines.

The highest expansion has been measured in most cases on the top side of the cube.

4 DISCUSSION

Table 5 summarizes the categorization of different European aggregates based on test results according to RILEM AAR-2 [3], AAR-3 [4], AAR-4 [5], the German fog chamber method [6] and the Norwegian methods [7], that were taken from the technical reports 3.2 [12] and 3.3 [13] and on the performance in the field site test. At this stage of the field site tests the comparison of the different test methods indicates that aggregates that are categorised as “normally” reactive (reported reactivity in structures: timescale 5-20 years) and show expansion $> 0.04\%$ and/or cracks $\geq 0.20\text{mm}$ in the field site after 2 to 3½ years can be reliably identified with all methods as reactive.

Aggregate D2 that is in the group of “slowly” reactive aggregates (reported reactivity in structures: timescale > 20 years) showed some signs of a deleterious ASR and was identified as reactive with all methods. In case of D2 not all of the methods agreed with the field site results. So far D2 has reacted in southern and middle Europe, but it was not possible to identify the reactive sand that contains sea gravel semi-dense flint with the concrete prism tests clearly. The reason is unclear. This sand should belong to the first group of aggregates (aggregate combinations that react in “normal” timescale).

The testing time of 3½ years is too short to draw conclusions for the other slowly and the non-reactive aggregates that were partly tested as marginally reactive with some concrete prism test methods. To get final results the tests have to be continued.

It can be assumed that the high expansions and crack width can be attributed to a deleterious ASR that has taken place in the concrete cubes. Final confirmation will be given by the investigation of thin sections at the end of the field site tests.

The field site tests showed that a deleterious ASR can take place in all European countries from Norway to Spain and it occurs independently of the climate condition (see figure 5), although the speed of the ASR is higher in hot climates (AIDICO) than in medium (VDZ, BRE) or cold climates (SP, SINTEF). Thus a reactive aggregate could cause damage faster in southern than in northern Europe (see figure 5 and 6).

The small cracks with a width of 0.05 mm that were found on most cubes are presumably due to shrinkage.

5 CONCLUSIONS

- After 3 to 3½ years of exposure at different European outdoor exposure sites all concrete samples containing reactive aggregates that react in normal timescale in structures (5-20 years) show significant signs of a deleterious alkali silica reaction like expansion > 0.04% and/or cracks with widths ≥ 0.20mm. Only a few concretes containing slowly reactive aggregates (timescale > 20 years) show indications that a deleterious ASR is possibly going to happen. The concrete compositions with “non-reactive” aggregates exhibit no sign of cracking and expansion.
- The field site tests were carried out in various climate zones representative for Europe in order to take into account the influence of different environmental conditions. However, the results indicate that a deleterious ASR occurs in the same way in northern and in southern Europe with the difference that the reaction occurs earlier in southern Europe probably due to the higher mean temperature.
- It is surprising that the specimens exposed only to ambient rainfall show more often high expansion than the specimens partly submerged in water.
- Specimens were stored alongside a highway in Sweden to study the additional influence of alkali supply under severe conditions. So far there is no difference in the performance of the concrete cubes stored in a nearby forest (without alkali supply) and alongside the highway (with alkali supply).
- The field site test will be continued in the future with yearly measurements.

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TABLE 1: Aggregate combinations tested in the field site.

<i>Sample number</i>	<i>Origin</i>	<i>Aggregate details</i>	<i>Combinations *</i>
B1	Western Belgium	Silicified limestone	C + F
B1	Western Belgium	Silicified limestone	C + NRF
D2	Denmark	Sea gravel semi-dense flint	F + NRC
F1	France (Seine Valley)	Gravel with flint	C + NRF
F2	France	Non-reactive limestone	C + F
G1	Germany (Upper Rhine Valley)	Gravel with siliceous limestone and chert	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. rocks	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; NRF = non-reactive fine aggregate

TABLE 2: Field sites and climatic classification.

<i>Participant</i>	<i>Field site</i>	<i>Climate abbreviation</i>	<i>Climate classification according to Köppen*</i>
AIDICO	Valencia-Paterna, Spain	Csa	Mediterranean climate with wet winter and dry summer
Cesi Ricerca	Milano, Italy	Cfb, close to Cfa	Maritime temperate climate close to humid subtropical climate with moderate humidity and relatively warm to hot summer
VDZ	Düsseldorf, Germany	Cfb	Maritime temperate climate with moderate humidity and mild temperature
BRE	Watford, United Kingdom	Cfb	Maritime temperate climate with moderate humidity and mild temperature
SP	Highway between Borås and Gothenburg, Sweden	Dfb	Boreal forest climate with moderate humidity and relatively warm summer, additional alkali supply due to de-icing salts in winter
SP	Borås, Sweden	Dfb	Boreal forest climate with moderate humidity, cold winter and relatively warm summer
Norcem	Brevik, Norway	Dfb	Boreal forest climate with moderate humidity, cold winter and relatively warm summer
SINTEF	Trondheim, Norway	Cfc, close to Dfb	Maritime temperate climate with moderate humidity and mild temperature, relatively cold summer

*The Köppen climate classification (<http://koeppen-geiger.vu-wien.ac.at/>) is one of the most widely used climate classification systems. It is based on the concept that native vegetation is the best expression of climate, thus climate zone boundaries have been selected with vegetation distribution in mind. It combines average annual and monthly temperatures and precipitation, and the seasonality of precipitation.

TABLE 3: Maximum average values of expansion measured at 6 sets of embedded reference points and crack width of cubes stored partly immersed in water on different European outdoor exposure sites.

<i>Sample no.</i>	<i>Wet storage</i>	<i>Data</i>	<i>Laboratory/country</i>							
			<i>SINTEF</i>	<i>Norcem</i>	<i>SP Forest</i>	<i>SP Road</i>	<i>BRE</i>	<i>VDZ</i>	<i>Cesi Ricerca</i>	<i>AIDICO</i>
	<i>Combination</i>		<i>N</i>	<i>N</i>	<i>S</i>	<i>S</i>	<i>GB</i>	<i>D</i>	<i>I</i>	<i>ES</i>
B1	C+F	Cracks		0.30	0.20	0.15		0.30		0.50
		Exp.		0.131	0.138	<i>0.106</i>		0.158		0.159
B1	C+NRF	Cracks	0.25		0.20		n. d.		0.50	1.50
		Exp.	0.183		0.177		0.197		0.241	<i>0.244</i>
D2	F+NRC	Cracks	0.05		0.05	0.05	n. d.			1.10
		Exp.	0.004		0.017	<i>0.008</i>	0.038			0.286
F1	C+NRF	Cracks					n. d.		0.05	
		Exp.					< 0.0		0.014	
F2	C+F	Exp.		0.00	0.05	0.05		0.05		0.00
		Cracks		0.016	0.013	0.005		0.006		<i>0.018</i>
G1	C+NRF	Cracks	0.05					0.10	0.00	
		Exp.	0.029					0.089	0.096	
It2	C+F	Cracks		0.00					0.05	
		Exp.		0.012					0.013	
N1	C+NRF	Cracks	0.05		0.05	0.10	n. d.	0.05		0.15
		Exp.	0.011		0.012	<i>0.014</i>	0.052	0.066		0.088
N2	C+NRF	Cracks		0.20			n. d.			
		Exp.		0.006			0.018			
N4	C+F	Cracks		0.00				0.05	0.00	
		Exp.		0.006				0.013	0.006	
S1	C+F	Cracks		0.00	0.05	0.05		0.05		0.00
		Exp.		0.015	0.006	<i>0.007</i>		0.014		0.010
UK1	C+F	Cracks	0.10		0.05	0.05	n. d.			0.00
		Exp.	0.012		0.015	<i>0.013</i>	0.023			0.114
P1	C+NRF	Cracks			0.05				0.00	
		Exp.			0.008				0.028	

Exp. = maximum expansion of cubes in % that occurred after the new “zero” measurement in June 2005
Cracks = maximum crack width of cubes in mm that occurred in approx. 3 to 3½ years of testing
n. d. = no data provided
Italic data = Value is based only on 2 or 4 sets of embedded reference points
C = coarse aggregate; F = fine aggregate; NRC = non-reactive coarse aggregate; NRF = non-reactive fine aggregate

TABLE 4: Maximum average values of expansion measured at 6 sets of embedded reference points and crack width of cubes stored “dry” only exposed to ambient rainfall on different European outdoor exposure sites.

			<i>Laboratory/country</i>							
<i>“Dry storage”</i>			<i>SINTEF</i>	<i>Norcem</i>	<i>SP Forest</i>	<i>SP Road</i>	<i>BRE</i>	<i>VDZ</i>	<i>Cesi Ricerca</i>	<i>AIDICO</i>
<i>Sample no.</i>	<i>Combination</i>	<i>Data</i>	<i>N</i>	<i>N</i>	<i>S</i>	<i>S</i>	<i>GB</i>	<i>D</i>	<i>I</i>	<i>ES</i>
B1	C+F	Cracks		0.40	0.20	0.20		0.30		0.40
		Exp.		0.196	0.173	0.176		0.190		0.174
B1	C+NRF	Cracks	0.30		0.20		n. d.		0.80	0.50
		Exp.	0.160		0.248		0.208		0.310	0.192
D2	F+NRC	Cracks	0.05		0.05	0.05	n. d.			1.20
		Exp.	0.006		0.018	0.015	0.070			0.288
F1	C+NRF	Cracks					n. d.		0.05	
		Exp.					< 0.0		0.004	
F2	C+F	Exp.		0.00	0.05	0.05		0.05		0.00
		Cracks		0.009	0.002	0.007		0.007		0.001
G1	C+NRF	Cracks	0.15					0.10	0.00	
		Exp.	0.035					0.115	0.111	
It2	C+F	Cracks		0.00					0.00	
		Exp.		0.010					0.019	
N1	C+NRF	Cracks	0.10		0.10	0.10	n. d.	0.05		0.10
		Exp.	0.010		0.014	0.013	0.046	0.079		0.123
N2	C+NRF	Cracks		0.20			n. d.			
		Exp.		< 0.0			0.012			
N4	C+F	Cracks		0.00				0.05	0.00	
		Exp.		0.012				0.012	0.017	
S1	C+F	Cracks		0.00	0.05	0.05		0.05		0.00
		Exp.		0.014	0.006	0.005		0.014		0.031
UK1	C+F	Cracks	0.10		0.05	0.05	n. d.			0.00
		Exp.	0.016		0.032	0.014	0.060			0.056
P1	C+NRF	Cracks			0.05				0.00	
		Exp.			0.006				0.010	

Exp. = maximum expansion of cubes in % that occurred after the new “zero” measurement in June 2005
Cracks = maximum crack width of cubes in mm that occurred in approx. 3 to 3½ years of testing
n. d. = no data provided
Italic data = Value is based only on 2 or 4 sets of embedded reference points
C = coarse aggregate; F = fine aggregate; NRC = non-reactive coarse aggregate; NRF = non-reactive fine aggregate

TABLE 5: Summarized test results of different aggregates in tests according to RILEM AAR-2, -3 and -4, in some regional tests (German fog chamber method [6] and Norwegian methods [7]) and the performance in the field site.

Sample no.	Details	Combination	Reactivity/evaluation				
			AAR-2	AAR-3	AAR-4/ AAR-4 alt	German/ Norwegian	Field site test
Reactive aggregate combinations in "normal" timescale (5-20 years)							
B1	Silicified limestone	C+F	R	R	R/R	R/R	R
B1	Silicified limestone	C+NRF	R	R	R/R	-/-	R
G1	Gravel with siliceous limestone and chert	C+NRF	R	R	R/R	R/-	R
N1	Cataclasite	C+NRF	R	R	R/R	R/R	R
UK1	Greywacke	C+F	R	R	R/R	R/R	R
"Slowly" reactive aggregate combinations (> 20 years)							
D2	Sea gravel semi-dense flint	F+NRC	R	NR/MR?	R/MR	-/-	R
It2	Gravel with quartzite and gneiss	C+F	R	NR	R/R	-/-	n. r.
N2	Sandstone	C+NRF	R	R	-	-/R	possibly reactive
N4	Gravel with sandstone and catacl. rocks	C+F	R	MR	R/-	MR/MR	n. r.
"Non-reactive" aggregate combinations							
F1	Gravel with flint	C+NRF	NR	NR	NR/NR	NR/-	n. r.
F2	Non-reactive limestone	C+F	NR	NR	NR/NR	NR/NR	n. r.
S1	Gravel with porphyritic rhyolite	C+F	R	NR	MR/-	NR/MR	n. r.
P1	Silicified limestone	C+NRF	NR	NR	MR/MR	-/-	n. r.
<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 AAR-4 alt = The concrete prisms are wrapped and stored in individual containers instead of a storage above water in individual containers. * = one result strongly reactive, second non-reactive ** = the evaluation of the preliminary results from the field sites is based on measurements of crack widths after about 3½ years of exposure and of expansions during the last 2 years (the expansion measurements were restarted in 2005 due to problems with the zero measurements at some field sites).</p>							

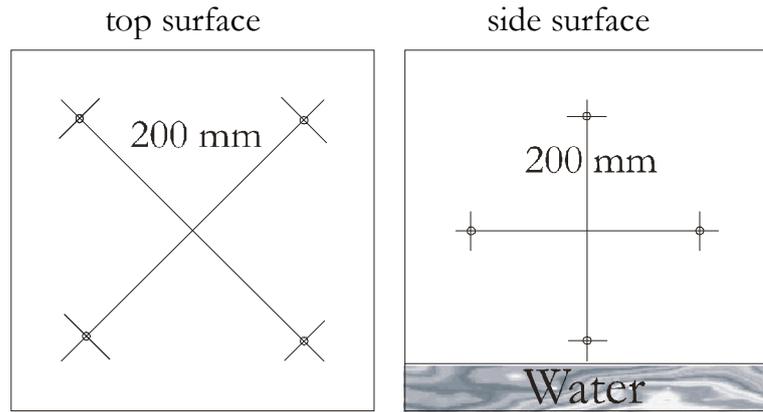


Figure 1: Positions of reference studs on concrete cube surfaces.

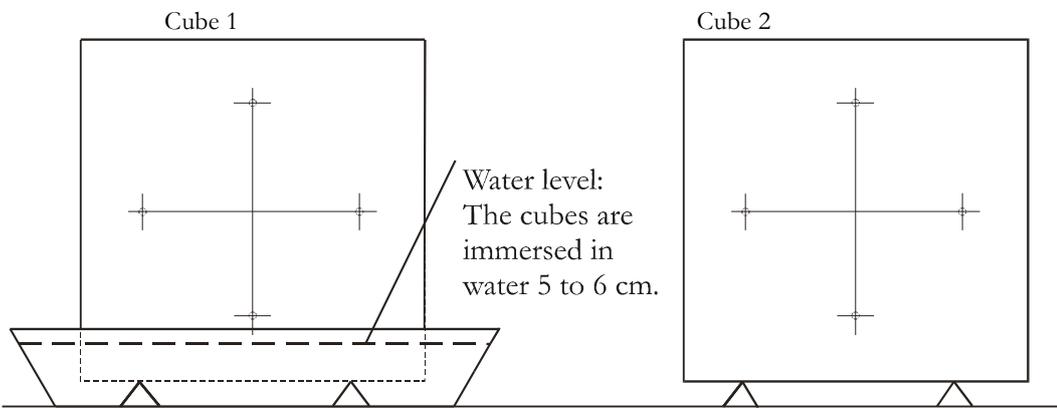


Figure 2: Storage of cubes at the field site.

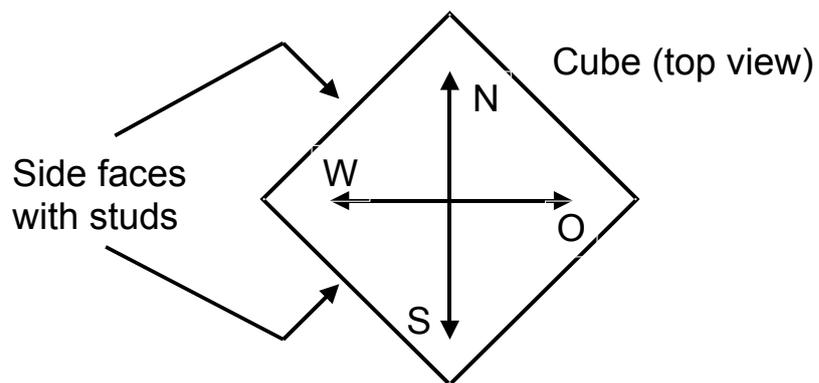


Figure 3: Orientation of cubes.

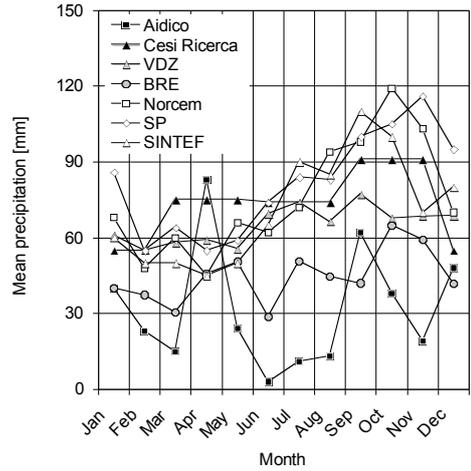
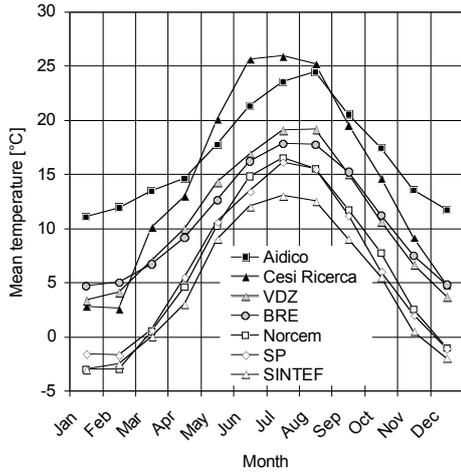


Figure 4: Mean temperature and precipitation at different field sites.

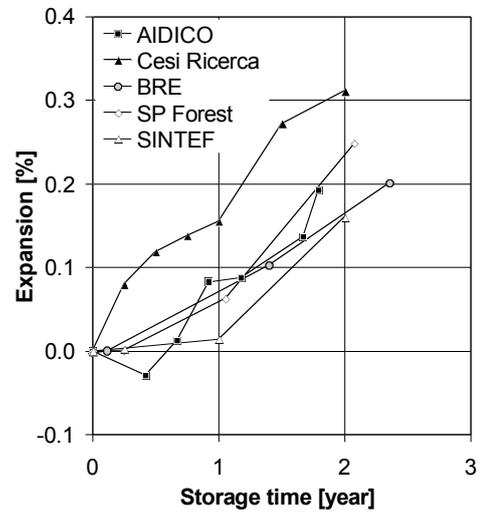
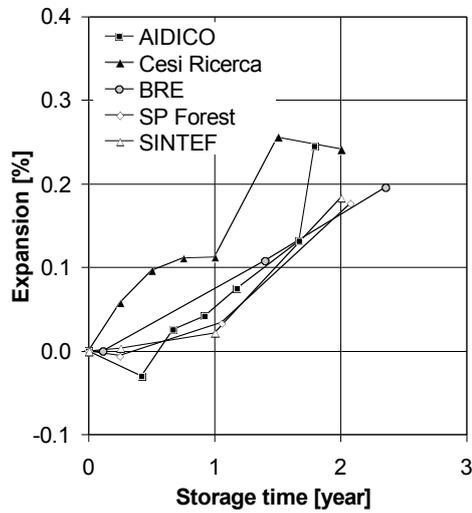


Figure 5: Mean expansion of concrete cubes B1(C+NRF);
left: stored partly immersed in water; right: only exposed to ambient rainfall.

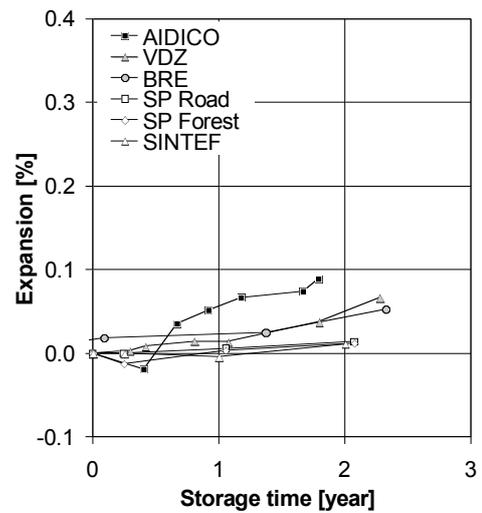
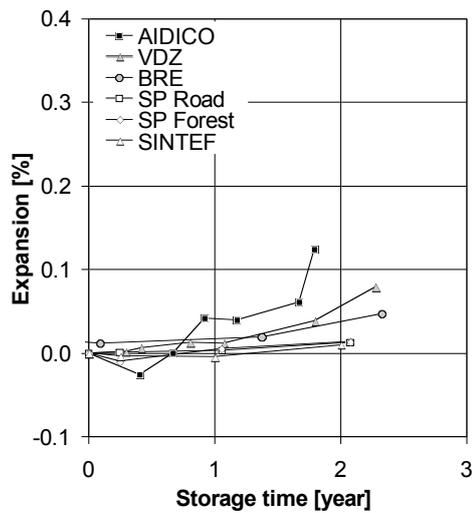


Figure 6: Mean expansion of concrete cube N1;
left: stored partly immersed in water; right: only exposed to ambient rainfall.