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Evaluation of laboratory test methods for assessing the alkali-reactivity potential of aggregates by field site tests

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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 (eight tests were included). One hundred concrete cubes made with 13 different European aggregate combinations were stored on eight different European field sites to compare their expansions with the laboratory test results. All highly reactive aggregate combinations caused significant expansion of concrete cubes within the first six years on all field sites from Norway to Spain. These and the non-reactive aggregate combinations were correctly identified with all laboratory tests. Concrete cubes with moderately reactive aggregate combinations expanded very slowly and mainly in the outdoor exposure sites with warm climate conditions. The RILEM test method AAR-4.1 (60°C accelerated concrete prism test) and the Norwegian concrete prism test at 38°C seem to be best suited to identity the potential reactivity of moderately reactive aggregate combinations.

KEY WORDS: Accelerated mortar bar test; Climate; Concrete prism test; Field site test; Moderately reactive aggregates.

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RESUMEN: *Evaluación de los métodos de ensayo de laboratorio para evaluar la reactividad alcalina potencial de los áridos mediante ensayos de campo.* Se realizaron pruebas de campo para evaluar la fiabilidad de los ensayos desarrollados por RILEM y algunos ensayos regionales para evaluar la reactividad alcalina potencial de los áridos (se incluyeron ocho ensayos). Se almacenaron 100 cubos de hormigón fabricados con 13 combinaciones diferentes de áridos europeos, en ocho emplazamientos europeos distintos, para comparar sus expansiones con los resultados de las pruebas de laboratorio. Todas las combinaciones de áridos altamente reactivos provocaron una expansión significativa de los cubos de hormigón durante los primeros seis años en todos los emplazamientos de campo, desde Noruega hasta España; éstas y las combinaciones de áridos no reactivos se identificaron correctamente con todas las pruebas de laboratorio. Los cubos de hormigón con combinaciones de áridos moderadamente reactivos se expandieron muy lentamente y principalmente en los lugares de exposición exterior con condiciones climáticas cálidas. El método de ensayo RILEM AAR-4.1 (ensayo acelerado de prisma de hormigón a 60°C) y el ensayo de prisma de hormigón noruego a 38°C parecen ser los más adecuados para identificar la reactividad potencial de las combinaciones de áridos moderadamente reactivos.

PALABRAS CLAVE: Prueba acelerada de barra de mortero; Clima; Prueba de prisma de hormigón; Prueba de campo; Áridos moderadamente reactivos.

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1. INTRODUCTION

The European “PARTNER” project (2002-2006) 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 (1, 2). As part of it, field site tests have been carried out since 2004 to assess the reliability of the different test methods to evaluate the alkali-reactivity potential of aggregates. One hundred concrete cubes made with 13 different European aggregate combinations were stored on eight different European field sites in order to compare their expansions with the laboratory test results. This document presents the results of field site tests after 15 years of outdoor exposure to evaluate the four expansion test methods developed by RILEM (3) and four regional concrete test methods (Table 1). The regional tests are the German concrete method, the Norwegian concrete prism test, the Danish mortar bar test TI-B51 and the Danish Chatterji method.

All aggregates were also analysed petrographically according to RILEM AAR-1 within the “PARTNER” project (3). The results are described in (2) and not considered in this paper.

2. MATERIALS AND METHODS

2.1 General

To evaluate the reliability of different laboratory test methods, concrete cubes were produced with the same concrete mixture as used in the prisms for the accelerated laboratory testing. The concrete cubes with 300 mm lateral length were stored at different outdoor exposure sites in Europe. The expansion and the maximum crack width were determined periodically at approximately the same temperature (15°C) in spring and autumn.

2.2 Materials

Thirteen aggregate combinations (of the 22 aggregate types included in the laboratory test program) 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

Table 1. Summary of test methods. Extracted from (2).

Test method	Brief outline of method
RILEM AAR-2 Accelerated mortar bar method (4, 5)	Mortar bars made with the aggregate and a reference high alkali cement are stored in 1M NaOH at 80ºC and their expansion monitored over a 14 days period. Two alternative prism sizes are used; 25x25x285 mm^3 (AAR-2.1) or 40x40x160 mm^3 (AAR-2.2).
RILEM AAR-3 Concrete prism method (6)	Expansion test for 12 months. Wrapped concrete prisms, (75±5)x(75±5)x (250±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 in a constant temperature room at 38°C and measured at 20°C. This wrapped version was withdrawn by RILEM TC 219-ACS in 2010. A revised test procedure without wrapping was published in 2016 (7).
RILEM AAR-4.1 Accelerated concrete prism method (8)	Expansion test for 20 weeks. Concrete prisms, (75±5)x(75±5)x(250±50) mm^3, made with the aggregate and a reference high alkali cement (1.25% ± 0.05% sodium oxide eq.) are stored in individual containers within a reactor at 60°C and measured at 20°C.
Draft RILEM AAR-4 Alt. Accelerated concrete prism method (9)	Accelerated expansion test for 20 weeks. Wrapped concrete prisms, (75±5)x(75±5) x (250±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 in a constant temperature room at 60°C and measured at 20°C. This draft wrapped version of the 60°C accelerated concrete prism test (ACPT) was withdrawn by RILEM TC 219-ACS in 2010.
German concrete method (10)	Test duration of 270 to 273 days. Concrete prisms (100x100x500 mm^3) and one cube (300 mm^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 (11)	Accelerated expansion test for 12 months. Concrete prisms (100x100x450 mm^3) made with the aggregate and a reference high alkali cement are stored in individual containers in a room at 38°C and 100% relative humidity and measured at 20°C.
TI-B51 - The Danish mortar bar test (12)	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 (13)	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.

(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 aggregates were grouped into three categories according to their reported field behaviour:

- non-reactive aggregates (green),
- moderately reactive aggregates that react in timescales of 15 to 50 years (yellow) and
- highly reactive aggregates that react in timescales of 5 to 20 years (red).

The former classes for “slowly” and “normally” reactive aggregates in (2) are re-named in this paper as “moderately” and “highly” reactive aggregates to comply with classes in North America (14-16).

The former RILEM standard cement CEM I 42,5 R provided by NORCEM AS, Norway was used for preparing the concrete. The total alkali content of the cement was 1.26 mass% Na_2O-equivalent.

2.3 Mixture proportions

Concrete was made with 440 kg/m³ cement, and the water to cement ratio was 0.50. The air content was approximately 1.5 vol.-%; no air-entraining agent was added to the concrete mix. In case of inappropriate workability of the concrete (slump < 20 mm) a superplasticizer was added. In accordance with the RILEM test method AAR-3 and AAR-4.1 the aggregate combination consisted of one of the following (see Table 2):

- 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 mass-% fines (0 to 4 mm) and 70 mass-% coarse aggregates: 30 mass-% 4 to 10 mm and 40 mass-% 10 to 20 mm.

2.4 Methods and Exposure Conditions

Two concrete cubes with 300 mm lateral length were produced for each field site and each aggregate combination (Table 3). All the cubes representing one concrete mix (i.e. one aggregate combination) were cast at one laboratory (generally in the country of origin of the aggregate) and transported to all

Table 2. Aggregate combinations tested in the field site. Extracted from (2).

Sample number	Origin	Aggregate details	Combinations *	Reported reactivity in structures
F1	France (Seine Valley)	Gravel with flint	C + NRF	Non-reactive. No evidence of damage in structures, but considered to be potentially reactive with clear pessimum effect.
F2	France	Non-reactive limestone	C + F	Non-reactive
It2	Italy (Piemont region)	Gravel with quartzite and gneiss	C + F	Moderately reactive, damage between 15 to 50 years
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	
P1	Portugal	Silicified limestone	C + NRF	
B1(RF)*	Western Belgium	Silicified limestone	C + F	Highly reactive, damage between 5 to 20 years
B1			C + NRF	
D2	Denmark	Sea-dredged sand semi-dense flint	F + NRC	
N1	Norway (middle)	Cataclasite	C + NRF	
G1	Germany (Upper Rhine Valley)	Crushed gravel with siliceous limestone and chert	C + NRF	
UK1	United Kingdom	Greywacke	C + F	

* C = coarse aggregate
F = fine aggregate
NRC = non-reactive coarse aggregate (= F2C)
NRF = non-reactive fine aggregate (=N3F)
RF = reactive fine aggregate (=B1F)

Table 3. Aggregate combinations tested in the different field site.

Aggregate	Reactivity	Borås Forest	Borås Highway	Trondheim	Brevik	Watford	Düsseldorf	Milan	Valencia
F1	Non-reactive					F1-Wa		F1-Mi	
F2		F2-BF	F2-BH		F2-Br		F2-Du		F2-Va
IT2	Moderately reactive				IT2-Br			IT2-Mi	
N2					N2-Br	N2-Wa			
N4					N4-Br		N4-Du	N4-Mi	
P1		P1-BF						P1-Mi	
S1		S1-BF	S1-BH		S1-Br		S1-Du		S1-Va
B1(RF)	Highly reactive	B1(RF)-BF	B1(RF)-BH		B1(RF)-Br		B1(RF)-Du		B1(RF)-Va
B1		B1-BF		B1-Tr		B1-Wa		B1-Mi	B1-Va
D2		D2-BF	D2-BH	D2-Tr		D2-Wa			D2-Va
G1		G1-BF		G1-Tr			G1-Du	G1-Mi	
N1		N1-BF	N1-BH	N1-Tr		N1-Wa	N1-Du		N1-Va
UK1		UK1-BF	UK1-BH	UK1-Tr		UK1-Wa			UK1-Va

the other laboratories (field test sites). After production, the cubes were kept in the moulds for one day, de-moulded and stored in a room at 20 ± 2°C and ≥ 95% relative humidity (or were covered with moist fabric) for 6 days before being transported to the different field sites (Figure 1).

At the different field sites, each institute that participated in this research installed two pairs of reference studs into the top surface and into the two adjacent side faces, before the cubes were exposed outdoors. Most laboratories pre-drilled holes before gluing the studs. 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 (Figure 2).

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. Since 2010 (6 years after exposure) the trays were refilled only by rainfall instead of a manual control of the water level due to the fact that there were no significant differences between the two conditions. The concrete cubes were stored on eight different field sites that were selected to cover all climates in Europe (2). Figure 3 gives the mean monthly temperature and precipitations for each field site.

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 conducted at the field site at temperatures around 15°C and preferably in periods with rather stable temperatures over a 24-hour period and with limited sunshine. The mean expansions of the three side faces are presented in Figure 4.

Figure 1. Location of the eight outdoor exposure sites, with two field sites near Borås.

3. RESULTS AND DISCUSSION

3.1 Field site tests

Figure 4 shows the mean expansion of selected cubes from four field sites Milan, Italy (Mi), Düsseldorf, Germany (Du), Brevik, Norway (Br) and Trond-

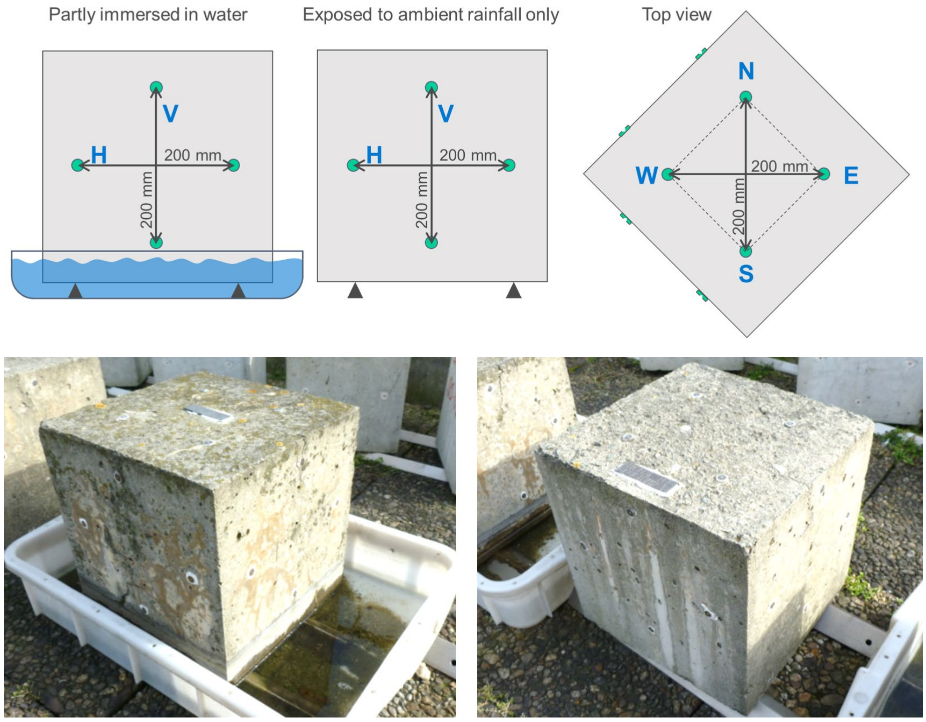

FIGURE 2. Orientation and storage of cubes at the field site; the left cube partly immersed in water; the right cube placed on furring strips.

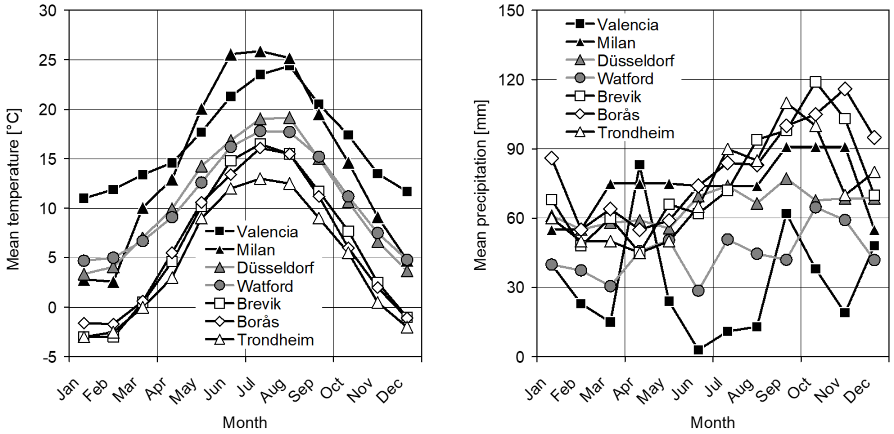

FIGURE 3. Mean temperature and precipitation at different field sites. Extracted from (2).

heim, Norway (Tr). The cubes were stored "partly immersed in water". For comparison with laboratory test results, one cube for each aggregate combination that was reliably measured up to 15 years was selected. The selection was necessary because some cubes weren't measured constantly over the entire 15 year period. The colours used in all the figures correspond to the aggregate reactivity (see 2.2).

All highly reactive aggregates expanded within the first six years at the four field sites and showed high expansions from 0.3% to 1.6% after 15 years. In the mild and warm climates of Düsseldorf, Germany (Du) and Milan, Italy (Mi) the expansion rates decreased after some years, whereas in cold climates like Trondheim, Norway (Tr) (Figure 5) and Borås, Sweden (shown in (2)) the expansion still continued, probably due to frost that damages the concrete further once ASR has caused sufficient cracks (17).

The cubes with the moderately reactive aggregates expanded considerably slower with expansions of about 0.09% to 0.22% after 15 years.

The cubes with the non-reactive aggregate F2 neither expanded at any field site nor showed significant cracking. However, the Damage Rating Index (DRI) determined on polished sections and qualitative damage assessment performed on thin sections revealed that an alkali-silica reaction (ASR) occurred to a small extent (18). The gravel with flint F1 was considered to be potentially reactive with clear pessimum effect (2). Deviating from (19), the gravel with flint F1 is classified as non-reactive in this paper because damage in structures was not evident (2) and the cubes in Milan only showed very little expansions of 0.05 % after 9 years and no significant cracking. Thin section analysis also revealed for this concrete little ASR compared to the majority of moderately and all highly reactive aggregates (18). Based on experiences from other field site tests, a limit value of 0.050% is applied to identify non-reactive aggregates (17).

For the following laboratory-field-correlations, the mean laboratory test results of all participating laboraties were used. Some results were excluded in the case they turned out to be unreliable and if the laboratory was unexperienced with the test method.

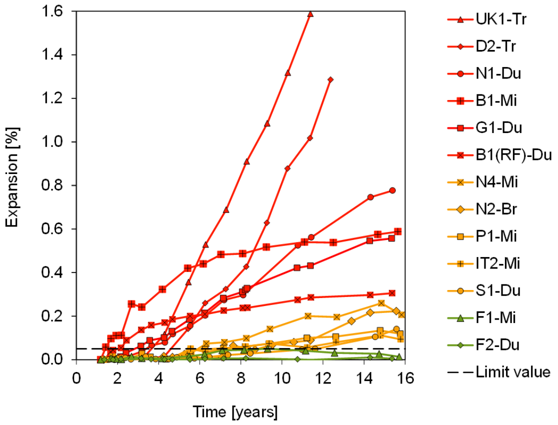

FIGURE 4. Mean expansion of concrete cubes located at different field sites in Europe; cubes were partly immersed in water, limit value of 0.050% as applied in (17).

3.2 RILEM AAR-2.1 and AAR-2.2 – Accelerated mortar bar test

Both versions of the AMBT (AAR-2.1 and AAR-2.2) were able to reliably distinguish between non- and highly reactive aggregates (Figure 6). It also identified the majority of the moderately reactive aggregates. The expansion of the Portuguese silicified limestone (P1) was below the acceptance limit value with both prism sizes. However, the very slowly reacting Swedish Gravel with porphyritic rhyolite (S1) behaved very differently depending on the prism size. It passed with the long thin prisms (AAR-2.1) and failed with the short fat ones (AAR-2.2).

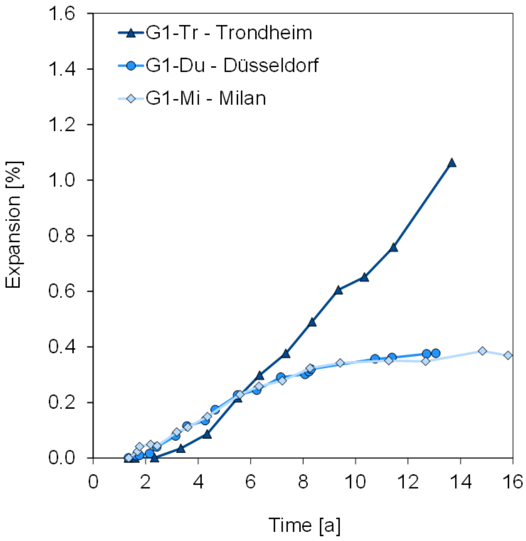

FIGURE 5. Mean expansion of cubes with the same concrete mix with aggregate G1 (G1-Tr, G1-Du and G1-Mi) located at three different field sites; cubes were placed on furring strips.

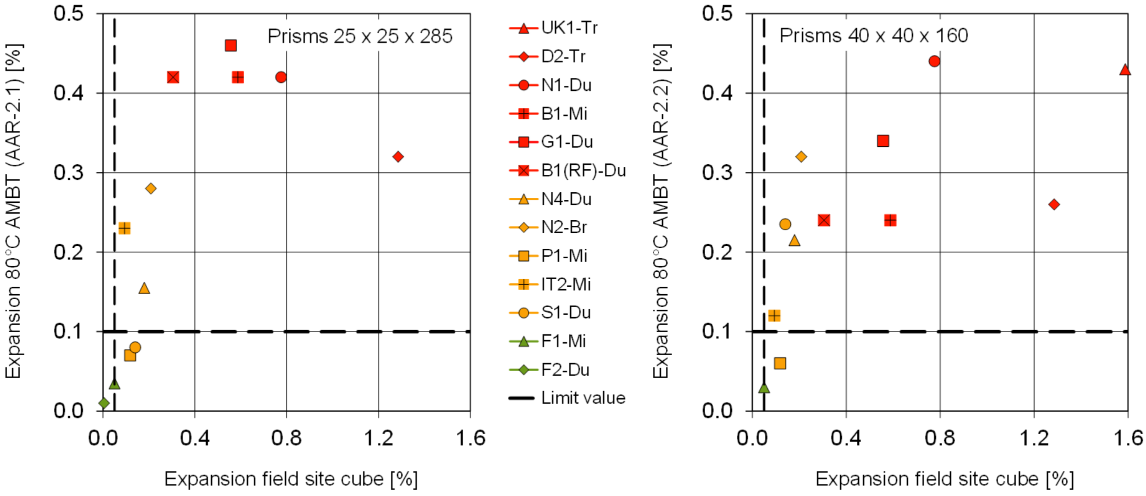

FIGURE 6. Mean expansion of concrete cubes located at different field sites in Europe (partly immersed in water) and the corresponding mean expansions of mortar bars after 14 days of storage in 1N NaOH in the 80°C AMBT according to RILEM AAR-2.1 (left, prisms 25 mm x 25 mm x 285 mm) and RILEM AAR-2.2 (right, prisms 40 mm x 40 mm x 160 mm). Data of laboratory tests (2).

3.3 RILEM AAR-3 and AAR-4.1 – Concrete prism test and accelerated concrete prim test

The concrete prism test methods AAR-3 and AAR-4.1 were effective in distinguishing between the non- and highly reactive aggregates (Figure 7 and Figure 8). In general, the highly reactive aggregates showed expansion above 0.16% in AAR-3 and between 0.10% and 0.20% in AAR-4.1. An exception is the flint containing sand D2 that showed only little expansions in the laboratory tests and even passed AAR-3.

Looking at the moderately reactive aggregates, the two versions of RILEM test method AAR-4.1 were detecting its reactivity potential more reliably, if the limit value of 0.03% after 20 weeks as proposed in (3) is applied. AAR-3 failed in identifying the slowest reacting aggregates P1, S1 and IT2, whereas N4 expanded just above the proposed acceptance limit value of 0.05% after 52 weeks (3). The AAR-4.1 was far better, and displayed the reactivity potential of four of the five moderately reactive aggregates. Only P1 was close to the limit value of 0.03%. The results confirm the RILEM-proposed acceptance limit of 0.03% (3) and suggest an assessment after 20 instead of 15 weeks. Otherwise, S1 would be classified as non-reactive. P1, S1 and IT2 are the slowest reacting aggregates in this comparison (no figures).

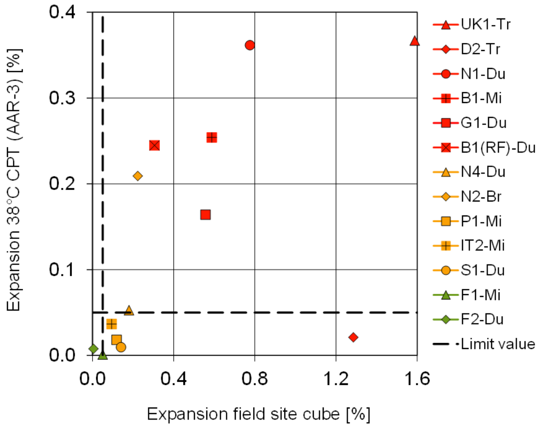

Figure 7. Mean expansion of concrete cubes located at different field sites in Europe (partly immersed in water) and the corresponding mean expansions of concrete prisms in the RILEM AAR-3 38°C CPT (wrapped version) after 52 weeks. Data of laboratory tests (2).

3.4 German and Norwegian concrete test methods

As for RILEM AAR-3 and AAR-4.1, the German and the Norwegian concrete test methods were able to distinguish between non- and highly reactive aggregates (Figure 9). However, the German method failed to identify the moderately reactive aggregates. Even the additional 300 mm-cube didn't show maximum crack widths ≥0.20 mm (not shown) for these aggregates. The overall expansions were lower compared with AAR-3, probably caused by a higher alkali leaching rate in the German fog chamber.

Compared with AAR-3 and the German method, the Norwegian CPT had the best match with the field performance of the cubes. It correctly displayed the alkali-reactivity potential of the three tested moderately reactive aggregates, even for the very slowly reacting S1. This can probably be attributed to the bigger prisms (100 x 100 x 450 mm^3) and less alkali leaching compared to AAR-3 (75 x 75 x 250 mm^3) (20).

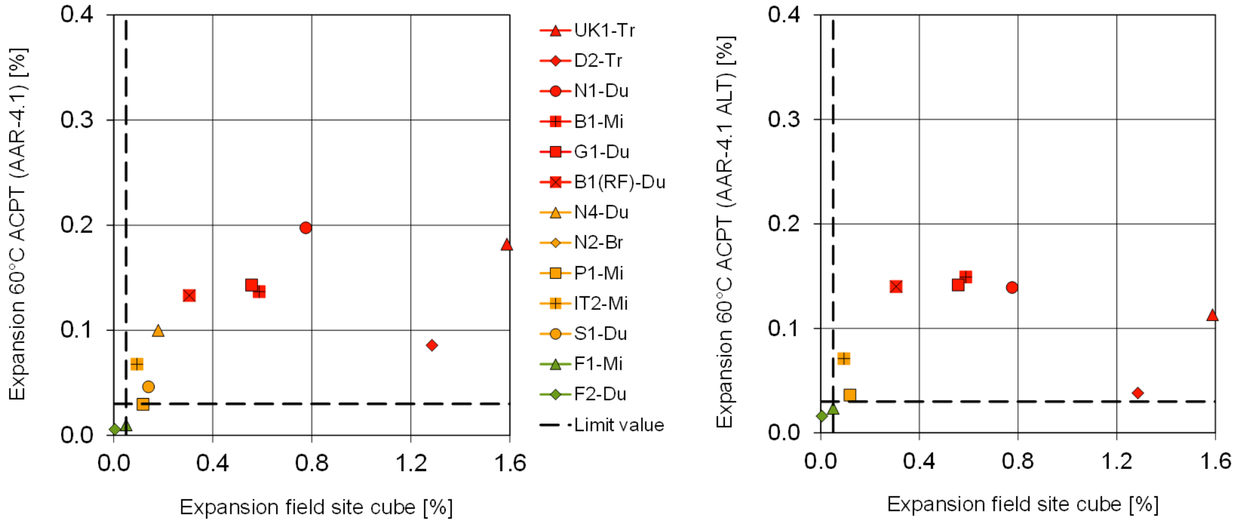

Figure 8. Mean expansion of concrete cubes located at different field sites in Europe (partly immersed in water) and the corresponding mean expansions of concrete prisms in the RILEM AAR-4.1 60°C ACPT after 20 weeks (left) and the alternative wrapped version (right). Data of laboratory tests (2).

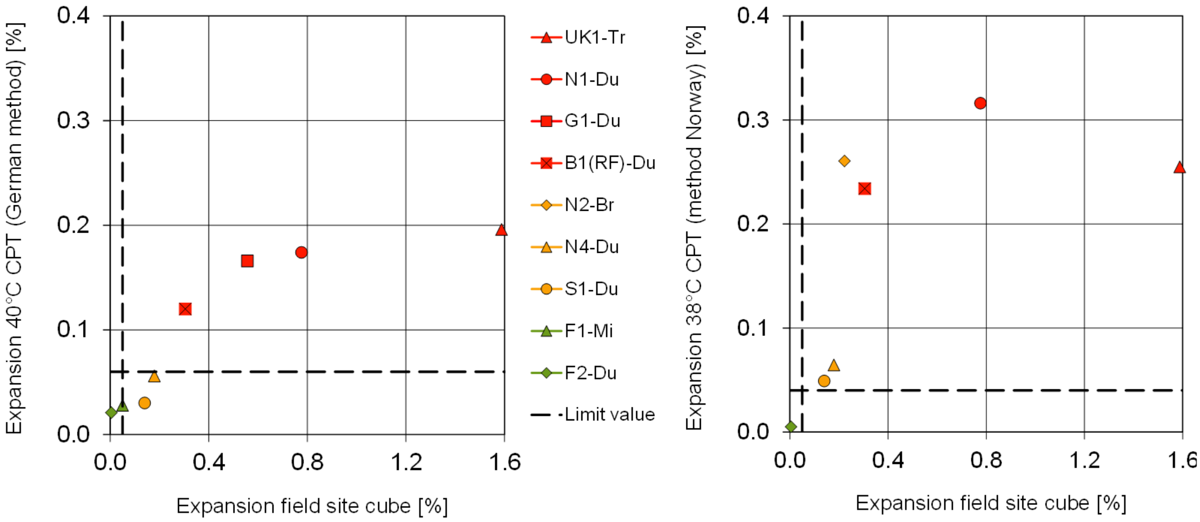

FIGURE 9. Mean expansion of concrete cubes located at different field sites in Europe (partly immersed in water) and the mean expansions of concrete prisms in the 40°C CPT (German method) after 9 months (left) and in the 38°C CPT (Norwegian method) after 52 weeks (right). Data of laboratory tests (2).

3.5 Danish mortar bar test TI-B51 and the Danish Chatterji method

In the Danish mortar bar test TI-B51, the expansion after 20 and 52 weeks is used for classifying aggregates into three alkali-reactivity classes. The names of the classes below are used in Figure 10 instead of the original ones described in the method:

- Non-reactive: Expansion <0.04% after 20 weeks
- Moderately reactive: Expansion <0.1% after 20 weeks and >0.1% after 52 weeks
- Highly reactive: Expansion >0.1% after 20 weeks

The TI-B51 was able to show successfully the reactivity potential of the non-reactive F1 and all highly reactive aggregates, but underestimated the reactivity potential of the moderately reactive aggregates N2, P1, IT2 and S1 (Figure 10). Furthermore, the classes used in this paper compared with the classes described in the procedure of TI-B51 differ a lot. Except for B1, the four other highly reactive aggregates were classified as moderately reactive according to the limit values for TI-B51.

The result of the Danish Chatterji method is a calculated Δ-value that is shown in Figure 11. The results suggest that Δ-values of 19 and higher are indicating a potential reactivity of the aggregate. Highly reactive aggregates revealed Δ-values between 30 and 50. Exceptions are aggregates with flint like F1 and D2. The non-reactive F1 gave a very high Δ-value and the highly reactive D2 had a very low one

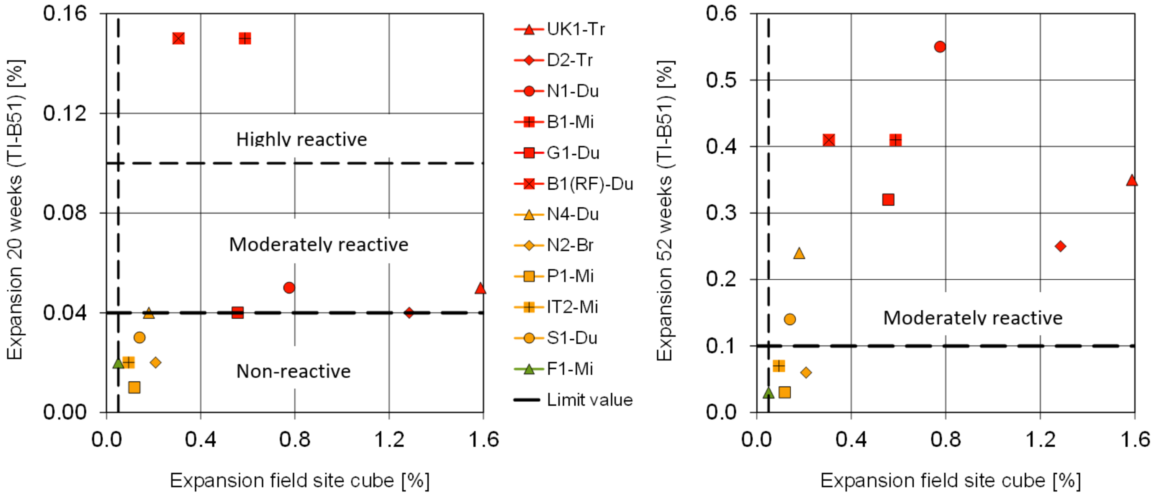

FIGURE 10. Mean expansion of concrete cubes located at different field sites in Europe (partly immersed in water) and the mean expansions of mortar bars in the Danish mortar bar test (TI-B51) after 20 (left) and 52 weeks (right). Data of laboratory tests (21).

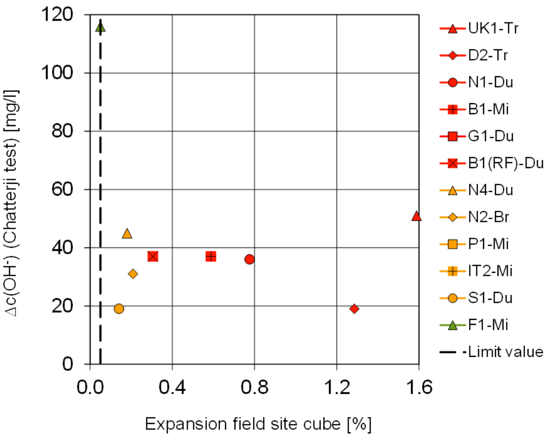

FIGURE 11. Mean expansion of concrete cubes located at different field sites in Europe (partly immersed in water) and the Δ of the hydroxide ion concentration in the Chatterji test. Data of laboratory tests (21).

compared to the other highly reactive aggregates.

4. CONCLUSIONS

The European "PARTNER" project (2002-2006) evaluated the reliability of four RILEM concrete prism tests and four regional test methods to assess the alkali-reactivity potential of aggregates. In addition, field site tests with concrete cubes produced with 13 different aggregate combinations were carried out for comparison with the laboratory results. After about 15 years of outdoor exposure, the main conclusions from this research are as follows:

- None of the two non-reactive aggregates showed any signs of ASR in the outdoor exposure sites.
- Highly reactive aggregate combinations caused significant expansion of concrete cubes at the field sites in Norway, Germany and Italy within the first six years of storage.
- All five moderately reactive aggregate combinations (timescale of reaction 15 to 50 years based on field experience) showed signs of damaging ASR.
- Once a deleterious ASR has occurred frost could probably further damage the concrete.
- The field site tests confirm that all laboratory tests correctly identified highly reactive and non-reactive aggregate combinations. However, of the RILEM test methods, AAR-4.1 seems to be best suited to identity the potential reactivity of moderately reactive aggregate combinations. The results confirm the limit value of 0.03% after 20 week instead of 15 weeks.
- The Norwegian concrete prism test at 38°C was also reliably identifying the moderately reactive aggregate combinations, probably due to reduced alkali leaching of the prims compared to RILEM AAR-3.

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