DEVELOPMENT OF AN ASR PERFORMANCE TEST: PRELIMINARY RESULTS FROM A PHD STUDY

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Abstract

This PhD study has aimed to evaluate whether concrete prism tests (CPTs) developed for assessment of alkali-silica reactivity (ASR) of aggregates might be suitable for general ASR performance testing of concrete. The effects of various pre-treatment and storage conditions on the following parameters important for development of ASR have been studied: concrete porosity, internal moisture state, transport properties and alkali leaching. The study has also given input to the work in the "Performance testing" task group of RILEM TC-219 ACS where the objective is to develop a reliable performance testing concept.

This paper gives an overview of the laboratory program and presents some preliminary results. The parameter that has shown to have highest influence on the measured prism expansion is rate and extent of alkali leaching, but for lower water-to-cementing-materials ratio (w/cm) also the concrete internal moisture state and the transport properties significantly influence the rate of the ASR expansion.

Keywords: alkali silica reaction, performance testing, alkali leaching, moisture state

1 INTRODUCTION

1.1 Background

Since ASR was recognised as a durability challenge more than 70 years ago by Stanton [1], several comprehensive research projects have focused on test methods for determining the alkali reactivity of aggregates and corresponding acceptance criteria. In Europe, only national ASR aggregate tests are available today. As part of the international harmonisation of such aggregate tests, two previous RILEM technical committees (TC 106-AAR, 1998–2000 and TC 191-ARP, 2001–2006) have proposed and validated three RILEM concrete prism tests (CPTs) for classifying the alkali reactivity of aggregates: AAR-3, 2000 (wrapped prisms) [2], AAR-4.1 "Standard" (unwrapped prisms), 2006 [3] and AAR-4.1 "Alternative" (wrapped prisms), 2006 [3], in addition to recommendations for how to use these test methods and interpret the results (RILEM AAR-0, 2003 [4]). These draft RILEM methods have been developed further by RILEM TC 219-ACS (2007–2012) and are planned to be published in a special issue of Materials and Structures during 2012. The revisions made are partly based on findings in the EU funded "PARTNER" research project where all the RILEM aggregate test methods were evaluated [5]. In USA and Canada, corresponding test methods exist (ASTM C1293-08b [6]; CSA A23.2-14A-04 [7].

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Internationally, various ways of controlling ASR are suggested (in addition to use of non-reactive aggregates): utilization of low-alkali cement, limiting the alkali content of the concrete, incorporation of supplementary cementitious materials (SCMs) or use of lithium salts. SCMs control expansion due to ASR by binding alkalis and limiting their availability for reaction with alkali–silica reactive aggregates [8]. The efficiency of the SCMs depends on their composition. Consequently, to be able to utilise alkali–silica reactive aggregates for production of durable concretes, the effects of various measures must be correctly identified by accelerated laboratory performance tests (or alternatively by relevant long-term field experience). Several such performance tests have been used worldwide for at least 15 years. However, the test conditions (e.g. temperature, alkali content, humidity) might differ from one test method to another. Thus, the results and conclusions from different test methods may vary widely.

1.2 Development of reliable ASR performance test methods

Main challenges

In 2006, Thomas et al. [9] provided a critical evaluation of different ASR performance test methods. The authors concluded that none of the currently available or commonly used test methods meet all the criteria for an ideal performance test.

The development of accurate and reliable performance tests for the production of durable concretes is a challenge. Several requirements must be fulfilled, some being somewhat contradictory. On the one hand the test methods should be inexpensive and rapid, calling for extremely accelerated test conditions. On the other hand a performance test should mirror the field performance of the actual concrete for more than 50 years lifetime. Another important requirement is the possibility to test job mixes with identical aggregate and concrete composition that will be used on actual projects. Use of mortar bars is in conflict with this latter requirement. According to Thomas et al. [9], other important requirements for an ideal performance test for ASR are:

• The test should be capable of determining the "critical" or "threshold" alkali content for specific aggregates, i.e. the alkali leaching problem must be solved to avoid the need for a boosted alkali level.

• The test should be capable of assessing all types of SCMs, lithium compounds and combinations of SCM and lithium, with cements of different alkali level.

RILEM TC 219-ACS

Today, research is going on in several countries with the aim to improve current ASR performance test methods and develop alternative tests. As part of the international harmonisation of ASR performance test methods, the "Performance testing" task group of RILEM TC 219-ACS is working on a performance testing concept with aim to develop one or more reliable ASR concrete performance test methods that might cover several applications/areas, ranging from combination of various aggregates with a standard CEM I binder up to the "ultimate goal" to document the alkali reactivity of any concrete recipe.

1.3 PhD study

A main aim of the PhD study, being part of the Norwegian COIN project (www.coinweb.no), has been to evaluate whether concrete prism tests developed for assessment of alkali-silica reactivity of aggregates might be suitable for general ASR performance testing of concrete. The study has been performed in close co-operation with the "Performance testing" task group of RILEM TC 219-ACS (all authors of this paper are members of this task group).

Literature review – assessment of parameters influencing laboratory performance testing

When developing an accelerated performance test, it is crucial theoretically to evaluate fundamental questions in order to ensure a satisfactory laboratory/field correlation. As a collaborating work between the PhD study and the work within the task group "Performance testing" in RILEM TC 219-ACS, a comprehensive literature review has recently been performed. In total, 12 authors contributed to the report that included about 250 references [10]. The main objective was to assess how various parameters might influence the laboratory/field correlation with respect to ASR performance testing, either directly or indirectly. The main findings in the literature survey and recommendations for performance testing have recently been summarised by Lindgård et al. [11]. These recommendations include precautions when testing various aggregates and binders, important factors to take into account during mix design, as well as possible influences on ASR expansion of various conditions during pre-storage and the ASR exposure. Additionally, the literature survey has identified several issues that need further research in order to develop a reliable performance test procedure.

Parameters focused on in the PhD study

Of the important parameters discussed in the literature review report [10] and paper [11], the PhD study has focused on the effect of "pre-treatment" and "ASR storage conditions" on:

• Porosity and internal moisture state of the concrete prisms.
• Concrete transport properties (with respect to diffusion of water and ions).
• Alkali leaching (rate and extent) from the concrete prisms during the ASR exposure.
• Concrete prism expansion (rate and ultimate expansion).

The "pre-treatment conditions", defined as the moisture conditions during pre-storage and the length of the pre-storage period at ambient temperature (up to the point of the initial (zero) length comparator reading), vary for various concrete prism tests used in the different countries.

Also the "ASR storage conditions" (i.e. moisture conditions, type of container, prism size, use of any wrapping, storage temperature, length of the storage period and addition of any external alkalis) might vary between various performance test methods used in the different countries.

To assess the influence of "pre-treatment conditions" and "ASR storage conditions" on the outcome of an ASR performance test, an extensive laboratory program has been performed. This paper gives an overview of the laboratory programme and the comprehensive supplementary testing for documentation. Furthermore, the paper presents some preliminary results.

2 THE TEST PROGRAMME

2.1 General

The PhD laboratory test programme has in total included 60 ASR test series (see Section 2.3), most of them by use of modified versions of the three RILEM aggregate CPTs (AAR-3, 2000 (wrapped prisms) [2] and AAR-4.1, 2006 (unwrapped and wrapped procedure) [3]). For comparison, also six test series with slightly modified versions of the Norwegian CPT [12] were included. This test method has been used in Norway for about 20 years, the last 15 years also for performance testing. Additionally, 12 test series with the ASTM C1293-08b CPT [6] (unmodified version) were incorporated in order to document any batch to batch variation and to establish a link to the comprehensive experiences in North America with this method.

In addition to the ASR testing, a comprehensive supplementary testing program for documentation of concrete properties of importance for development of ASR has been performed. The main parameters documented include internal moisture state, transport properties and alkali leaching.

2.2 Materials and mixture proportions

Two CEM I Portland cements, one high alkali and one low alkali, and a blended cement (CEM II-A/V) containing approximately 20% fly ash were used in the study (see Table 1). The aggregates used are defined in the Norwegian ASR regulations [12, 13] as “reference Norwegian aggregates” and consist of a non-reactive sand from Ardal and an alkali-silica reactive coarse aggregate, a crushed cataclasite, from Ottersbo. The aggregates were blended to produce a 60:40 coarse:fine ratio.

Details of the concrete mixtures produced are given in Table 2. The bulk of the testing was produced on a mixture containing 400 kg/m^3 of Portland cement with a water-to-cement ratio (w/c) of 0.45. The two CEM I cements were blended to produce an alkali content of 3.7 kg/m^3 Na_2Oeq. The alkali content was chosen with aim to reach an ultimate expansion of the reference test series lying on the ascending part of the “expansion versus alkali level curve” based on comprehensive testing at SINTEF [13].

To examine the impact of w/c, two additional concrete mixtures were cast with w/c of 0.30 and 0.60. The cement contents of these mixtures were modified to achieve the desired workability, but the alkali content of the mixes was maintained at 3.7 kg/m^3 Na_2Oeq by appropriate blending of the CEM I cements.

One mixture was produced with a water-to-cementing-materials ratio of w/cm = 0.45 using the blended cement containing 20% fly ash. The alkali content of this mixture was raised to 9.0 kg/m^3 Na_2Oeq to obtain an ultimate expansion of the "fly ash concrete mix" on the ascending part of the “expansion versus alkali level curve”.

2.3 ASR test procedures – test series

ASR concrete prism tests

All the five CPTs included in the study are designated for testing alkali-silica reactivity of concrete aggregates. Additionally, ASTM C-1293 CPT [6] and the Norwegian CPT [12] are frequently used for ASR performance testing. Main experiences from about 15 years of performance testing with the latter methods have recently been assessed as part of the PhD study [13].

The main differences between the selected five CPTs are exposure temperature (38°C or 60°C; only RILEM AAR-4.1 (both procedures), 2006 [3] uses the highest temperature), prism cross section (100x100 mm (only the Norwegian CPT) or 70-75x70-75 mm) and use of any wrapping (damp cotton cloth and polyethylene; only RILEM AAR-3, 2000 [2] and RILEM AAR-4.1 "Alternative", 2006 [3]).

Modification of the test procedures

Since the PhD study has focused on the effect of "pre-treatment conditions" and "ASR storage conditions" on the outcome of an ASR performance test, the standard versions of the concrete prism tests (except the ASTM C-1293 CPT [6]) have been slightly modified in order to investigate the effect on concrete properties important for development of ASR, extent of alkali leaching and ASR expansion. The technical background for the modifications is given in the recently published literature review paper [11].

During all the testing only deionised water has been used, i.e. as batched water, in the moist cotton cloth wrapping (if any) and in the storage containers.

For all test series each prism was always stored vertically in the storage container with the same prism end pointing upwards (marked with an arrow). This is in contrast to the description for the three RILEM CPTs and ASTM C-1293 CPT that prescribe the each prism should be turned at every reading (i.e. the prism end that has been pointing upwards in the container since the last reading should be pointing downwards until the next reading). The reason for this modification is to be able to document any variation in internal moisture state, extent of alkali leaching and extent of internal cracking over the prism height.

For all standard versions of the CPTs the readings of weight and length are taken after cooling the prisms for about 16 hours inside their storage container in a room kept at ~ 20°C. All readings in the modified versions of the various concrete prism tests were taken without cooling the prisms.

The following "pre-treatment" parameters and/or ASR storage conditions have been varied when modifying the RILEM AAR-3 CPT (2000, [2]) and the two RILEM AAR-4.1 CPT procedures (2006, [3]):

- The wrapping procedure (if any) was slightly modified, either by adding only half of the water content prescribed or by removing the prescribed polyethylene bag.
- The length of the "pre-storage" period was varied. The prisms were kept at ambient temperature until 1, 7 or 28 days after casting before being exposed to the ASR exposure temperature. However, for all test series the prisms were prepared for final storage (e.g. wrapped) and put into the storage container immediately after de-moulding (and any 0.5 h submersion) and the initial measurements of weight and length.
- Some prisms were pre-cured to simulate the curing temperature in a massive concrete structure.
- Some prisms were sealed.
- Some prisms were stored submerged in deionised water (in order to give the prisms maximum alkali leaching conditions).
- Some prisms were wrapped with cotton cloth saturated with a basic solution of strength pH 14.2 or 13.2, respectively (instead of using deionised water), in order to try to reduce the extent of alkali leaching.

2.4 Supplementary tests

In order to document properties of importance for initiation and progress of ASR, comprehensive supplementary testing has been an important part of the study. The following tests have been included:

- Alkali release from the aggregates
- Alkali leaching from the concrete prisms (rate and extent)
- Concrete porosities ("PF-method" [14])
- Moisture state (degree of capillary saturation, DCS [15], and relative humidity, RH)
- Relative diffusion coefficient [16].
- Electrical resistivity ([17], [18])
- Visual inspection (including photo documentation)
- Microstructural analysis (of polished – and thin sections + Scanning Electron Microscopy (SEM) analysis)

The documentation was performed at two points of time: four weeks after starting the ASR exposure (in order to document concrete properties in the early stage of the ASR test) and after ending the ASR exposure, i.e. after 39 weeks (all 60°C test series), 52 or 112 weeks (38°C test series).

The tests initiated after four weeks of ASR exposure were performed on an "extra prism" exposed to identical pre-treatment and ASR exposure conditions as the three parallel prisms in the same test series. The supplementary tests performed after ending the ASR exposure were executed on one of the three parallel prisms in each test series.

3 RESULTS

In this paper, only selected preliminary results are presented. Figure 1 shows expansion versus time curves for test series with the base concrete mixture (CEM I, w/c 0.45). The following main trends can be seen:

<u>Exposure temperature 60°C</u>:

- ✓ The ultimate expansion of the unwrapped prisms is several times higher than the ultimate expansion for the wrapped prisms. The increase in expansion for the unwrapped prisms from 13 to 26 weeks is significant (about 0.05 %), while the expansion from 26 to 39 weeks is low.

- ✓ Wrapped prisms show little increase in expansion in the period after 8-13 weeks of exposure.
- ✓ Wrapped prisms with only half of the prescribed water content added to the cotton wrapping (the two upper "wrapped curves") expand significantly more than the wrapped prisms with more water added.
- ✓ The test series submerged in deionised water during the whole exposure period reveals hardly any expansion at all.

Exposure temperature 38°C:

- ✓ All the eight test series tested according to ASTM C-1293 reveal almost identical expansion after 1 year, ranging from 0.254 to 0.279 %.
- ✓ The prisms tested according to the Norwegian CPT (with cross section 100x100 mm) reveal the highest expansion. With this method the increase in expansion from one to two years (upper dotted line) is relatively high (about 0.15 %).
- ✓ The prisms tested according to ASTM C-1293 (with cross section 70x70 mm) reveal significantly less expansion than the larger Norwegian CPT prisms. The increase in expansion from one to two years (the lower dotted line) is only about half of the increase the larger Norwegian CPT prisms gained.
- ✓ All the prisms tested according to ASTM C-1293 expand more after 39 weeks of exposure than comparable unwrapped prisms exposed to 60°C.
- ✓ After one year of exposure wrapped prisms always expand less than unwrapped prisms.
- ✓ For one of the test series with wrapped prisms the increase in expansion from one to two years (upper solid-drawn line) is relatively high (about 0.15 %).
- ✓ For the other wrapped test series exposed for two years the expansion is moderate after one year of exposure (lower solid-drawn line). The increase in expansion from one to two years is also modest (about 0.06 %). The main difference between the two wrapped test series is the length of the pre-storage period at 20°C. The test series represented with the upper curve was exposed to 38°C after 1 day, while the less expansive test series was stored at ambient temperature for 28 days before being exposed to 38°C.

Figure 2 shows the expansion versus time curves for all the test series with the binder CEM I and w/c of 0.30. Compared with the basis mixture (CEM I, w/c 0.45), the following can be observed:

Exposure temperature 60°C:

- ✓ Test series with w/c ratio 0.30 expand similarly as corresponding test series with w/c ratio 0.45. This is valid both for wrapped and unwrapped prisms.

Exposure temperature 38°C:

- ✓ Dramatically lower expansion for all the test series with w/c ratio 0.30 compared with the comparable test series with the basis binder (w/c 0.45).
- ✓ At w/c ratio 0.30 the wrapped prisms expand somewhat more than unwrapped prisms (in contrast to what was observed at w/c ratio 0.45).

4 DISCUSSION

The low spread in expansions revealed for the eight test series with the basis binder tested according to ASTM C-1293 CPT [6] indicates that the laboratory has been able to produce the same concrete composition from batch to batch. Thus, test series cast from different concrete batches can be compared.

In general, the results show that for the same concrete mix the rate of expansion and the ultimate expansion might vary enormously between "commercial" concrete prism tests that are supposed to give similar conclusions with respect to alkali reactivity. Further, the results show that by slightly modifying the "pre-treatment" and ASR exposure conditions, the expansions might be significantly affected.

In particular at exposure temperature 60°C the "pre-treatment" conditions hugely influence the ultimate expansion. Of the conditions varied the use of wrapping or not has shown to have the highest impact on the expansions revealed. Preliminary measurements of rate and extent of alkali leaching have shown that the rate of alkali leaching in the early age (0-4 weeks) is significantly higher for wrapped prisms, leading to a low ultimate expansion compared with unwrapped prisms. By storing the prism submerged in deionised water most available alkalis are leached out from the prisms, leading to very low expansion.

The alarming high difference in expansion between unwrapped and wrapped prisms at 60°C was presented at the RILEM seminar "Recent development in AAR" at the Azores in March 2010 [19]. The RILEM AAR-4.1 "Alternative" 60°C CPT (wrapped version) [3] was then immediately withdrawn on the RILEM TC 219-ACS meeting the following day. Even though less differences between wrapped and unwrapped prism have been observed at 38°C compared with 60°C, also the wrapping procedure in the RILEM AAR-3 (2000) CPT [2] has been removed. The storage and exposure conditions for the revised AAR-3 CPT [20] is now similar to the exposure conditions used in ASTM C-1293 CPT [6].

For the base mix, the larger Norwegian CPT prisms exhibited the highest expansion. This is due to less alkali leaching with increasing prism size. This is in accordance with previous findings by Bakker [21].

At exposure temperature 38°C, the test series with w/c ratio 0.30 revealed a dramatically lower expansion compared with the comparable test series with the basis binder (w/c 0.45). Preliminary results indicate that the main reason for this lower expansion is significantly lower internal RH and a denser concrete with slower diffusion of water and ions.

5 FURTHER RESEARCH

Based on the results from the PhD study an extensive research program including 113 test series has recently been initiated. The aim is to verify the laboratory/field correlation with various test set up / test procedures, in addition to document various aggregate/binder combinations ("what is safe to use?"). Two field exposure sites have been established, one at SINTEF in Trondheim and one at LNEC in Lisbon.

6 CONCLUSIONS

Based on the laboratory test programme with aim to study the effects of various pre-treatment and storage conditions on parameters important for development of ASR, the preliminary main conclusions are:

- For the same concrete mix the rate of expansion and ultimate expansion might vary hugely between "commercial" concrete prism tests that are supposed to give similar conclusions with respect to alkali reactivity.
- The parameter that has shown to have highest influence on the measured prism expansion is rate and extent of alkali leaching.
- At exposure temperature 60°C the rate of alkali leaching in the early age (0-4 weeks) is significantly higher for wrapped prisms, leading to a low ultimate expansion compared with unwrapped prisms.
- The difference in expansion between unwrapped and wrapped prisms is higher at 60°C compared with 38°C.
- For lower water-to-cementing-materials ratio (w/cm ratio) also the concrete internal moisture state and the transport properties significantly influence the rate of the ASR expansion.

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TABLE 1: Chemical composition (EN 196-2) of the two ordinary Portland cements (CEM I), Norcem Industri and Norcem Anlegg, and the fly ash cement (CEM II-A/V) Norcem StandardFA (wt%).

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Na_2O_e	P_2O_5	LOI[1]
Norcem Industri	19.61	4.87	3.48	61.03	2.83	3.81	1.11	0.51	1.24	0.15	2.44
Norcem Anlegg	20.06	4.67	3.31	63.06	2.01	3.40	0.39	0.34	0.60	0.16	2.24
Norcem StandardFA[2]	26.61	8.73	4.24	50.34	2.37	3.28	1.04	0.56	1.25	0.33	1.20

[1] Loss-Of-Ignition.

[2] Blended cement with a class F fly ash content 21.6 wt%. Manufactured by co-grinding clinker and fly ash.

TABLE 2: Composition of the four concrete mixes included in the study.

Materials (kg/m^3)			Binder composition			
			CEM I, 0.45	CEM I, 0.30	CEM I, 0.60	CEM II-A/V, 0.45
Cement	Norcem Industri		200	60	285	---
	Norcem Anlegg		200	490	30	---
	Norcem StandardFA		---	---	---	400
Aggregates (SSD[1])	Årdal 0/4		735	700	755	725
	Ottersbo	4/8	185	175	190	180
		8/11	365	350	375	360
		11/16	550	525	565	540
Deionised water (free) (excl. any water in the superplasticizer)			180	165	189	180
NaOH (solids)			---	---	---	5.2
Alkali content (kg Na_2Oeq per m^3)			3.7	3.7	3.7	9.0
Superplasticizer			If necessary, add until workable and stable concrete (aimed slump 120 mm)			
De-foaming agent			If measured air content is > 3.0 %, add until air content is reduced to < 3.0 %			

[1] Saturated surface dry condition

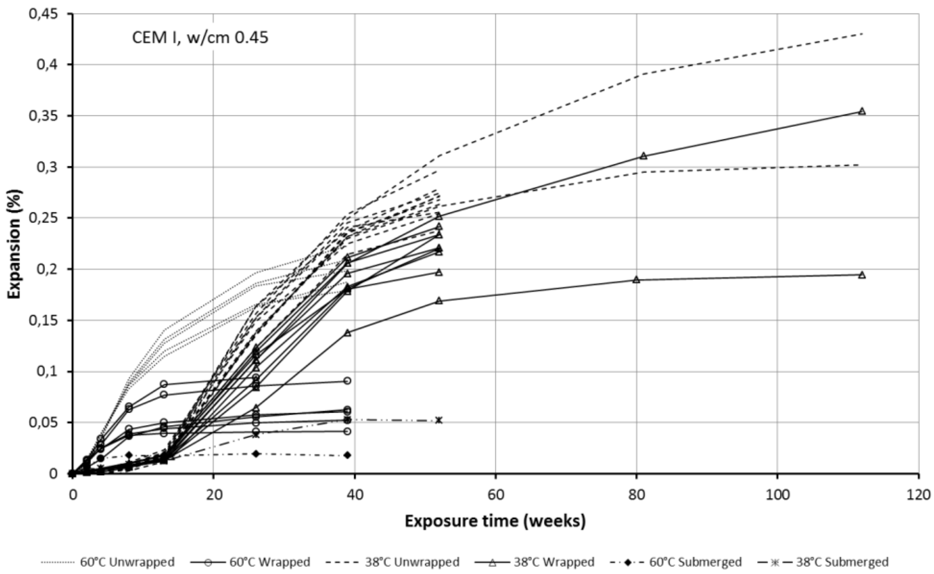

FIGURE 1: Expansion versus time for test series with the basis binder (CEM I, w/c 0.45).

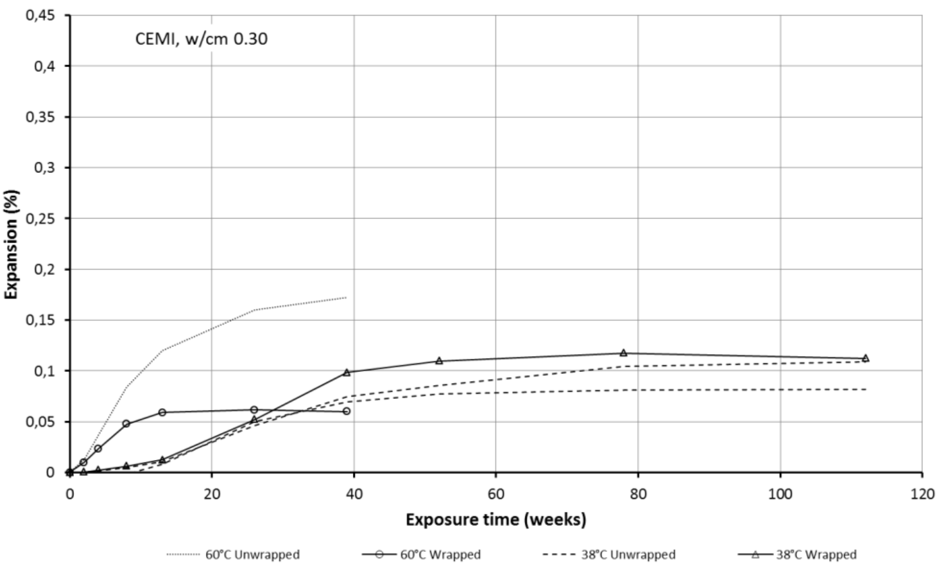

FIGURE 2: Expansion versus time for test series with the CEM I, w/c 0.30 binder.