A study on ASR in high strength lightweight aggregate concrete

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Abstract

Due to their silica content, most light weight aggregates (LWA) are potentially reactive. Despite this, knowledge regarding pre-testing ASR properties of LWA and LWA concrete (LWAC) is lacking internationally (a review was presented at ICAAR 2016). The accelerated mortar prism test shows that several LWAs can develop ASR, but it is still uncertain if this will ever occur in the field. The present work was done to bring more knowledge about ASR in typical high strength LWAC used in floating marine structures and bridges in Norway. These concretes contain LWA originated from expanded clay or shale, used as replacement of the coarse aggregate phase (> 4 mm), giving a concrete density of approximately 1900 kg/m^3. Both expanded shale and clay LWA were investigated, when used in a OPC (CEM I) concrete and in a concrete with CEM II B-M (18 % fly ash, FA) and 4 % silica fume. All concretes had alkali content of 5.0-5.5 kg/m^3 Na_2O_{eq} (CEM II concrete was "boosted" with NaOH). The concretes were tested according to the Norwegian Concrete Prism Test (NCPT), i.e. exposure to 38 °C, and RILEM AAR-4.1, i.e. exposure to 60 °C. Length and weight change as well as Young's Modulus of elasticity were measured. The results indicate ASR for both aggregates, in particular seen as a significantly higher weight increase than normally observed for concretes with normal density aggregates. Hence, statement given in the Norwegian guidelines (NB21 of the Norwegian Concrete Association) that LWA must be considered as reactive, seems to be valid.

Keywords: *ASR; LWAC; performance testing*

1. INTRODUCTION

High strength lightweight aggregate concrete (LWAC) has been used in many marine structures in Norway since the late 1980's. These are several cantilever bridges and two floating bridges (pontoons), as well as two offshore platforms for oil/gas exploitation; one floating and one gravity based. Typical for the concretes used in these applications is that LWA is used as the coarse fraction of the aggregate, giving the concrete a density of approx. 1900 kg/m^3 and a compressive strength of approx. 60 MPa. The LWA types used are expanded clay; "Leca" and "Liapor", or expanded shale; "Stalite".

Durability of these structures is of course of outmost importance, as well as maintaining the long-term density of the floating structures. In this context alkali-silica reactivity of LWA has been questioned. Therefore, in 2005, the Norwegian Public Roads Administration (NPRA) initiated a study on the matter. Results from the study was presented at ICAAR 2016 [1]. One part was to execute laboratory tests to assess the potential alkali-reactivity of the three LWAs mentioned above. Based on the results it was concluded: "**There is a possibility that the LWAs may develop ASR over time in real structures**. Performance of concrete prism tests linked to field exposed monitored cubes, in addition to field survey of structures and corresponding laboratory documentation are recommended". Another part was to examine existing Norwegian LWAC bridges built in the period 1987-2002 [2] where the above mentioned LWA types have been used. The examinations **did not reveal any ASR**. One reason for the latter could be that the alkali content in the concretes was rather low; estimated to be 2.2-4.5 kg/m^3 Na_2O_{eq}, i.e. below presently given Norwegian alkali limits for ASR (the limits are differing for different binders), and that 3-4 % silica fume was used. Anyway, the contradicting results from the two investigations show that more work is needed to answer the question if LWAs may develop ASR over time in real structures. Also, an international review of ASR in existing structures as well as in accelerated lab. tests revealed contradicting results [1].

Based on this, a laboratory program was initiated and executed within the Norwegian research project running from 2014 to 2019; "ASR – Reliable concept for performance testing". The purpose was to test ASR of typical LWAC for such structures but modified to give alkali content above presently used limits for ASR, and according to the most relevant test methods. The program and results are presented in this paper.

2. TEST PROGRAM

2.1 Materials

2.1.1 Light Weight Aggregate (LWA)

Two types were used, both pre-wetted as follows before mixing: The LWA was initially dry and then submerged in water for 24 hours followed by dripping to achieve a surface dry state:

- "Liapor 8", 4/8 mm (expanded clay) with particle density of 1570 kg/m^3 (SSD after 24 h in water)
- "Stalite", 4/13 mm (expanded shale) with particle density of 1550 kg/m^3 (SSD after 24 h in water)

2.1.2 Fine aggregate

Natural, partly crushed 0/4 mm fine aggregate from Årdal in Norway, supplied by NorStone. The dominant rock types are gneiss and granite. This non-reactive fine aggregate has previously been used in several Norwegian research projects [2, 3, 4].

2.1.3 Binders

Two binder types were used, both giving the concretes an alkali content corresponding to at least 5.0 Na_2O_{eq}; one pure OPC (CEM I acc. to EN197) and one blended cement combined with silica fume (according to NPRA specifications):

- "Norcem Industri"; CEM I, 400 kg/m^3, giving the concrete an alkali content of 5.5 kg/m^3 Na_2O_{eq}
- "Norcem STDFA; CEM II B-M (incl. 18 % FA intermixed), 370 kg/m^3, and addition of 4 % silica fume. The alkali content was "boosted" up to 5.0 kg/m^3 Na_2O_{eq} by adding 0.54 kg NaOH to the mixing water (all alkalis in the clinker, fly ash, silica fume and admixture are included)

2.1.4 Recipes

Recipes of the concretes are shown in Table 2.1. All concretes had w/b = 0.50 (same as described for the new RILEM performance test methods AAR-10 and AAR-11 – see 2.3) and were added an air-entraining admixture (Sika Aer-S) to obtain an air content of 5-6 %, and a superplasticizer (Sika SSP 2000) to give the target consistency (slump of 200 mm).

Table 2.1: Recipes (kg/m^3), fresh concrete density and slump

	Liapor CEM I	Stalite CEM I	Stalite CEM II
CEM I (OPC)	395	395	-
CEM II B-M (incl. 18 % FA)	-	-	368
Silica fume	-	-	15
Water (free)	197	197	200
Fine aggregate (0/4 mm)	763	666	679
Liapor 8 (4/8 mm)	511	-	-
Stalite (4/13 m)	-	548	558
Density (kg/m^3)	1870	1810	1825
Slump (mm)	210	190	200

2.2 Mixing and specimen preparation

The concretes were mixed in batches of 55 l in an action forced pan-mixer with a vertical shaft. All solid materials were mixed one min. before the water was added. Mixing time with water was approx. two min. after which the air-entraining agent and the superplasticizer was added to achieve the target air content (5-6 %) and consistency (approx. 200 mm). Total mixing time after water addition was ≈ 4 min.

Slump, density and air content were measured immediately after end of mixing.

All specimens (see 2.3) were cast in the respective molds simultaneously, using a casting ladle for compaction, and then stored covered under plastic sheets at room temperature until demolding approx. 24 hours after casting.

After demolding, the reference readings of weight and length of the prisms were performed, before all prisms were put into their respective storage containers that were directly placed at elevated temperature (see 2.3).

2.3 Testing

2.3.1 Overview

One aim of the before mentioned project is to increase the reliability of accelerated ASR lab. test methods for LWAC incl. calibration with real behavior in field. Therefore, two lab. test methods as well as a field test arrangement were included. The following tests were carried out:

- Expansion and weight change according to two ASR lab. test methods; NCPT (38 °C) [5] and RILEM AAR-4.1 (60 °C) [6]
- Young's Modulus of elasticity on the prisms above
- Expansion of field exposed 300 mm cubes (one stored at SINTEF's field exposure site in Trondheim and the parallel stored at LNEC in Lisbon; results are not yet available)

2.3.2 NCPT; the Norwegian Concrete Prism Test

In the Norwegian 38°C Concrete Prism Test (NCPT), three 100x100x450 mm prisms are stored in sealed containers over water, securing approx. 100 % relative humidity in the containers [5]. In the modified version used in this project, the prisms are measured at given intervals without any pre-cooling. According to the Norwegian ASR regulations [7] the critical expansion limits for aggregate testing is 0.040 % after 52 weeks of exposure. The corresponding critical limits for performance testing of concrete (primarily used for documentation of the ability of various SCM-containing binders to mitigate ASR) is 0.030 % after 52 weeks and 0.060 % after 104 weeks (the latter limit only valid for those binders that require two years testing time).

At every measuring point in time, a sample is collected from the water in the container for measuring the rate and extent of alkali leaching according to a procedure developed in the Norwegian COIN project [3]. The leaching results are not included in this paper.

2.3.3 RILEM AAR-4.1

In the modified version of the RILEM AAR-4.1 60°C CPT [6], three 70x70x280 mm prisms are stored in small, sealed containers over water, inside a reactor with water in the bottom, securing 100 % relative humidity inside and outside the small storage containers. In the modified version used in this project, the prisms are measured at given intervals without any pre-cooling. According to the recommendations by RILEM [6], a normal density aggregate giving less expansion than 0.030 % after 15-20 weeks of exposure can be regarded as non-reactive.

At every measuring point in time, a sample is collected from the water in the container for measuring the rate and extent of alkali leaching. The leaching results are not included in this paper.

2.3.4 Young's Dynamic modulus of elasticity

The Young's Dynamic modulus of elasticity (E_{dyn}) was measured for all the prisms at every measuring point in time for weight and expansion (see 2.3.2 and 2.3.3.). This supplementary testing has since 2007 been performed by SINTEF connected to several research projects. The main aim is to detect any internal cracking in the early period of any alkali-silica reaction. The experience with the method is very good; as soon as any internal cracking occurs, the E_{dyn} is reduced [3]. Later in the exposure period, it is normal to observe an increase in the E_{dyn}.

3. RESULTS

3.1 General

Previous results from ASR-testing of LWAC [1] reveal very high weight increase in relation to the expansion as compared with normal density (ND) aggregate concrete. An example is given in Figure 3.1. The normal density, highly reactive aggregate gives an extreme expansion, but moderate mass increase (approx. 2 %), while the LWACs (Stalite, Liapor, Leca and Liaver) show the opposite; low expansion but considerable weight increase. In fact, all LWAs tested, except Stalite, would be classified as "non-reactive" according to the measured expansion (less than 0.08 % at 14 days in the accelerated mortar bar test [5, 7]). However, the weight increase, corresponding to more than 150 kg/m^3, would not be accepted in practice. It confirms that a considerable amount of the ASR-gel is located in the porous LWA rather than in cracks in the cement paste, as referred to in [1] using foamed glass. This is of course particularly critical for structures of LWAC since maximum weight is a crucial requirement. Hence, this strongly suggests that weight change should be an important parameter to consider in addition to expansion to assess potential ASR of LWAC.

According to the Norwegian ASR regulations [7], no criteria is yet established concerning weight increase of LWAC. It is neither included any test procedures for assessing the reactivity of LWA or LWAC. Instead, it is recommended using the same mitigation measures as for ND aggregates. However, some other concrete test methods allow testing also of LWAs, for example ASTM C-1293 [8], without describing any other acceptance criteria than used for normal density aggregates.

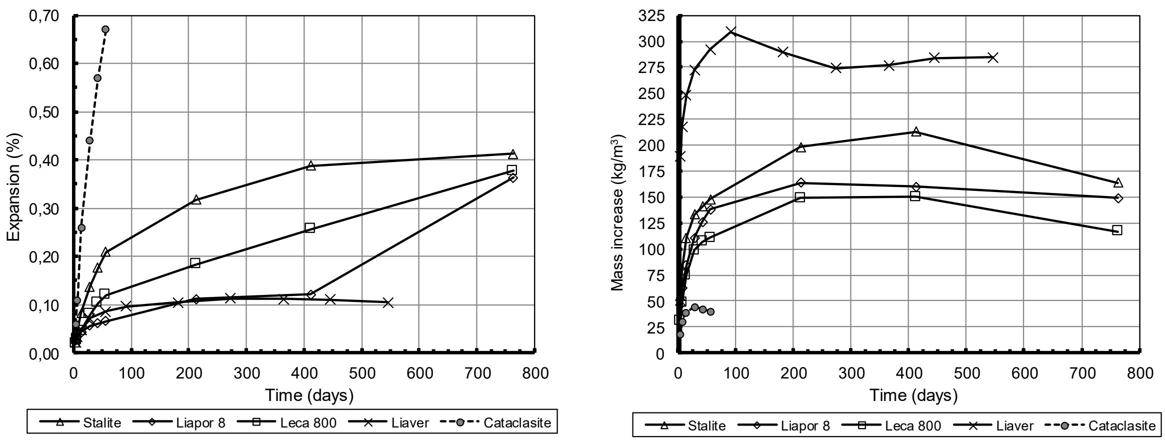

Figure 3.1: Expansion (left) and mass increase (right) of mortar bars submerged in 1M NaOH at 80°C [5]. The four LWAs are compared with the normal density alkali-reactive cataclasite aggregate [1]

3.2 Expansion and weight increase

3.2.1 Comparison of the two CPT methods

The main difference between the two CPT methods used is the exposure temperature, and the results confirm its importance; expansion and weight increase are considerably faster at 60 °C. Note that expansion at 38 °C after 145 weeks corresponds fairly well to the expansion at 60 °C after 26 weeks, but this is not the case for the mass increase that is much higher at 60 °C. At 80 °C (Figure 3.1), the same expansion is reached after less than 1 week. Also note that the expansion curves level off at an earlier point in time at 60 °C. Previous work shows that alkali leaching is the main reason for this levelling off [3]. Results from the alkali leaching measurements are, however, not assessed yet (will be performed after ending the laboratory testing).

3.2.2 Concretes with CEM I (pure OPC)

The present results (Figure 3.2) from the AAR-4.1 testing match well the outcome of [1], i.e. that Liapor is considered "non-reactive" and Stalite is considered "reactive" when considering expansion alone. According to the NCPT results, also Stalite is considered non-reactive. However, when considering weight increase, the picture is different: Testing of non-reactive normal density aggregates normally gives a weight increase of 0.2-0.3 % [3], mainly due to regular water absorption. It is well known that regular water absorption of LWAC similar to the ones used here, is in the same range. Hence, it may be assumed that weight increase beyond this is due to ASR-gel formation. Following this assumption, Stalite should be considered potentially reactive also according to the NCPT, and both Stalite and Liapor should be considered potentially reactive according to AAR-4.1.

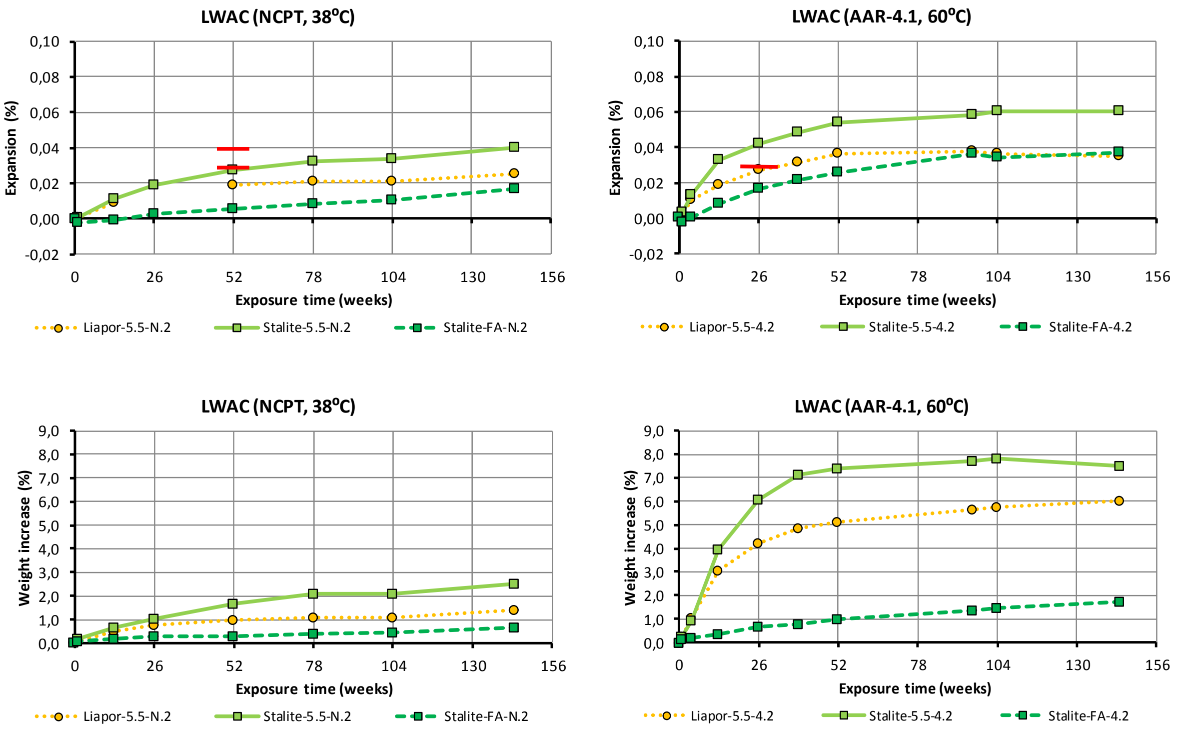

Figure 3.2: Expansion (upper) and weight increase (lower) of prisms testing according to the NCPT and AAR-4.1. Red lines indicate the respective recommended acceptance limits.

The Young's Dynamic modulus of elasticity (E_{dyn}) development follows a normal pattern (Figure 3.3 - see also section 2.3.4): The initial increase is hydration driven (exposed to elevated temperature already at 1 day of age). The typical damage indicator is seen as the drop in E_{dyn} beyond the initial phase. It is quite pronounced at 60 °C, which supports the relatively strong expansion in the same time period. The tendency can be seen also at 38 °C, but weaker. The subsequent increase of E_{dyn} is probably due to an "ASR-gel strengthening" [3]. Note however, that the E_{dyn} drop of the Liapor LWAC is larger (indication larger damage, i.e. more extensive internal cracking) than that of the Stalite LWAC in spite of less expansion and weight increase of the Liapor LWAC. A plausible explanation for this has not been found. A microscopical study can be performed after ending the laboratory testing for verifying the extent of internal cracking in the present concretes.

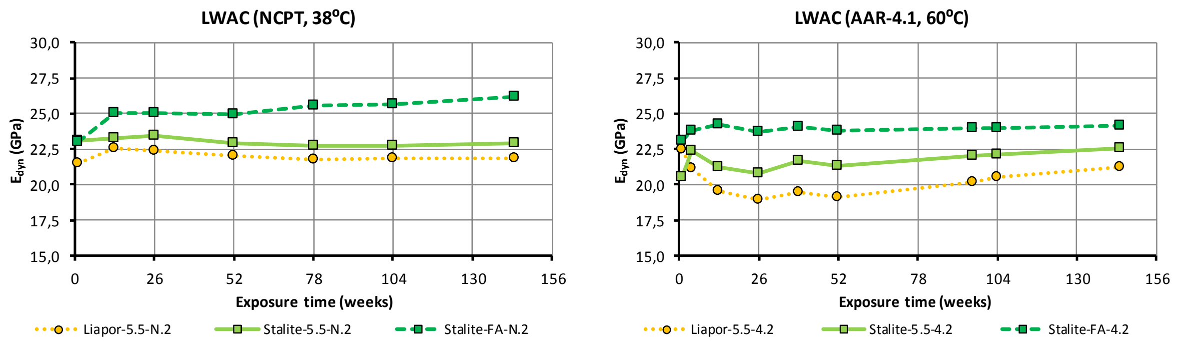

Figure 3.3: Development of Young's Dynamic modulus of elasticity (E_{dyn}) of prisms when exposed to NCPT and AAR-4.1 conditions, respectively.

3.3 Influence of combined fly ash and silica fume addition

The results clearly confirm the mitigating effect of fly ash (FA) and silica fume on ASR; comparing "Stalite CEM II" (including 18 % FA and additions of 4 % silica fume) with "Stalite CEM I" in Figures 3.2 and 3.3.

The mitigating effect on ASR for the LWAC with Stalite corresponds to earlier experiences with normal density, reactive aggregates, as reported by many researchers. Both expansion and weight increase are significantly lower when adding fly ash and silica fume, even if the Na_2O_{eq} is almost the same. This is supported by a hardly noticeable drop in E_{dyn}, in particular when exposed to 38 °C.

As for normal density, moderately reactive aggregates, the expansion and corresponding drop in E_{dyn} is higher for the 60 °C LWAC prisms compared to the LWAC prisms exposed to 38 °C.

4. CONCLUSIONS AND FURTHER WORK

Based on the limited test program with two LWAs, two binders and two concrete prism tests, the following conclusions can be drawn:

- A literature review shows that there are limited number of publications on ASR in LWAC. The few reports found reveal uncertainty if ASR in field might be a problem, and there are diverging results from laboratory tests
- Previous mortar bar tests (1 M NaOH, 80 °C) confirm that normal LWAs are potentially reactive
- Weight increase is an equally important parameter as expansion for assessment of ASR in LWAC, as it seems that a considerable amount of the ASR-gel is located in the porous LWA rather than in cracks in the cement paste. This may lead to an unacceptable increase of the density of the LWAC
- The NCPT and RILEM AAR-4.1 CPT reported here indicate ASR for both Liapor and Stalite concretes, mainly because of a high weight increase and a corresponding drop in Youngs's modulus of elasticity
- Addition of fly ash (FA; 18 %) and 4 % silica fume seem able to mitigate ASR of LWAC as for marginally, reactive, normal density aggregates
- The current Norwegian ASR regulations, NB21 [7], states that LWA must be considered to be alkali-reactive (for the time being) and that the same mitigation measures as used for normal density, reactive Norwegian aggregates can be used. The present results confirm that the statement is valid
- The results presented will be further assessed by microstructural analysis and correlated to future measurements of the field exposed cubes exposed in Trondheim and Lisbon

5. REFERENCES

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