Investigation of ASR Effects on the Load-Carrying Capacity of Reinforced Concrete Elements by Ultra-Accelerated Laboratory Test

J. Cao, N. Gowripalan, V. Sirivivatnanon, and J. Nairn

Abstract The alkali–silica reaction (ASR) can cause expansion, cracking, and degradation of the mechanical properties of affected concrete. Concerns about the safety of ASR-damaged reinforced concrete structures have driven the demand for studying the effects of ASR on residual load capacity of the deteriorated structure. Conventionally, field load testing methods are used to assess the residual load capacity of ASR-affected structures. In this study, a novel accelerated laboratory test using the LVSA 50/70 autoclave to accelerate ASR was applied to investigate the flexural and shear behavior of small-scale reinforced concrete beams affected by ASR. The specimens were subjected to three cycles of 80 °C steam curing at atmospheric pressure in the autoclave, with 60 h/cycle. Significant expansion and ASR damage were observed. Load carrying capacity tests on the small-scale reinforced concrete beams showed that, at the expansion levels achieved, the flexural capacity of the reinforced concrete beams was not significantly affected. Shear resistance of the reinforced concrete beams, however, was found to increase compared with their 28-day counterparts, which could be attributed to the prestressing effect due to ASR expansion. It appears that the multicycle 80 °C steam-curing autoclave test is suitable for investigating ASR deterioration of actual concrete mixes within a short period of time. ASR effects on the load carrying capacity of reinforced concrete elements at higher expansion levels, however, need further investigation.

Keywords Alkali–silica reaction (ASR) · Accelerated ASR test · Expansion · Load-carrying capacity

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W. Duan et al. (eds.), *Nanotechnology in Construction for Circular Economy*,
Lecture Notes in Civil Engineering 356,
https://doi.org/10.1007/978-981-99-3330-3_7

1 Introduction

The alkali–silica reaction (ASR) is one of the major durability problems for concrete structures and has been observed and studied for decades worldwide. Concerns about the safety of ASR-damaged reinforced concrete structures have driven the demand for studying the effects of ASR on the performance of the structure and the effect of ASR on residual load capacity of the deteriorated structure [1].

During the past decades of extensive research on ASR, field load testing on real structures was used to assess the residual load capacity of ASR-affected structures [2]. In addition, under controlled laboratory conditions, efforts were made to investigate the flexural and shear behavior of small-scale to full-scale reinforced concrete specimens [3–5]. Large-scale in-situ field exposure testing has also been conducted by different researchers [6]. Some researchers tested specimens in long-term tests with up to 10 years of field exposure to accelerate ASR [7]. These tests provided valuable results and knowledge on evaluating the residual load capacity of ASR-affected members. The long test duration of these field tests is required due to the reality that ASR damage takes a long time to develop in structures, but research needs call for rapidly and reliably producing ASR expansion in the laboratory with appropriate accelerated test conditions [1]. Hence, a reliable and rapid accelerated laboratory test to determine the risk of ASR expansion is needed.

In this study, we applied a novel accelerated test using an autoclave with 80 °C steam curing to study the flexural and shear behavior of small-scale reinforced concrete beams affected by ASR. The beams were longitudinally reinforced with two levels of reinforcement ratios. For simplicity, no shear reinforcement was used for the beams. Load carrying capacity tests on the small-scale reinforced concrete beams were conducted. Moreover, the mechanical properties of ASR-affected concrete under accelerated tests were investigated.

2 Methods

2.1 Materials and Mix Proportions

A general-purpose (Type GP) cement with equivalent alkali content (Na_2O_{eq}) of 0.50%, a nonreactive sand (Sydney sand), and a highly reactive dacite aggregate with a maximum nominal size of 20 mm as coarse aggregate, were used in the concrete mixes. As for the reinforcement, deformed bars with either 5-mm diameter (N5) or 8-mm diameter (N8) were used. In addition, to promote ASR in the accelerated test, technical-grade sodium hydroxide (NaOH) pellets with purity of 98% were used to raise the alkali content to 2.5% Na_2O_{eq} by mass of cement in the concrete. The NaOH pellets were pre-dissolved in a fraction of the mixing water 24 h prior to concrete mixing. The mix proportions for all of the small-scale reinforced concrete beams, cylinders and prisms were: cement: 520 kg/m^3; nonreactive sand: 620 kg/m^3; 20-mm highly reactive dacite aggregate: 1160 kg/m^3; water: 192.5 kg/m^3; and NaOH pellets: 13.69 kg/m^3.

2.2 Specimen Fabrication and Steam-Curing Procedure

We fabricated 12 small-scale reinforced concrete beams with a size of 100 × 100 × 340 mm; 6 beams were reinforced with two N5 deformed bars and the other 6 beams were reinforced with two N8 deformed bars as the main reinforcement. The reinforcement ratios for the two series of small-scale beams were 0.39% and 1.0%, respectively. No transverse reinforcement was provided for the beams. Concrete cover of the beams was maintained at 20 mm. Details of reinforcement of the beams are shown in Fig. 1.

Plain ∅ 100 mm (diameter) × 200 mm cylinders and 75 × 75 × 285 mm prisms were also cast. The cylinders were used for the mechanical properties test and the prisms were for free expansion measurement. Specimens were demolded after 24 h from casting. Thereafter, all specimens were stored in a humidity cabinet with temperature of 23 °C and relative humidity (RH) of 90%.

At the age of 28 days, a testing regime of 80 °C steam curing using an autoclave (Zirbus LVSA 50/70 with a chamber volume of 153 L) was used to accelerate ASR.

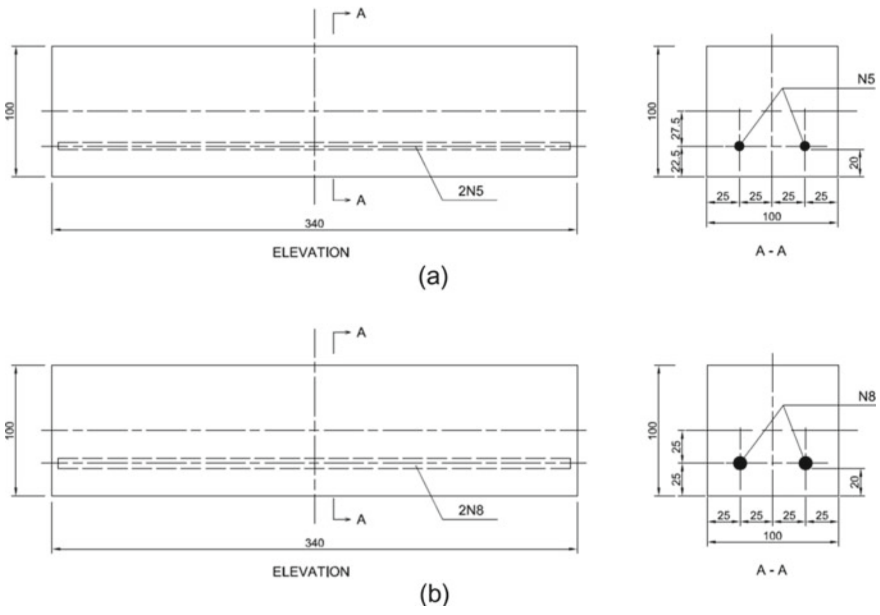

Fig. 1 Reinforcement details of small-scale reinforced concrete beams: **a** with two N5 deformed bars and **b** with two N8 deformed bars (all dimensions are in mm)

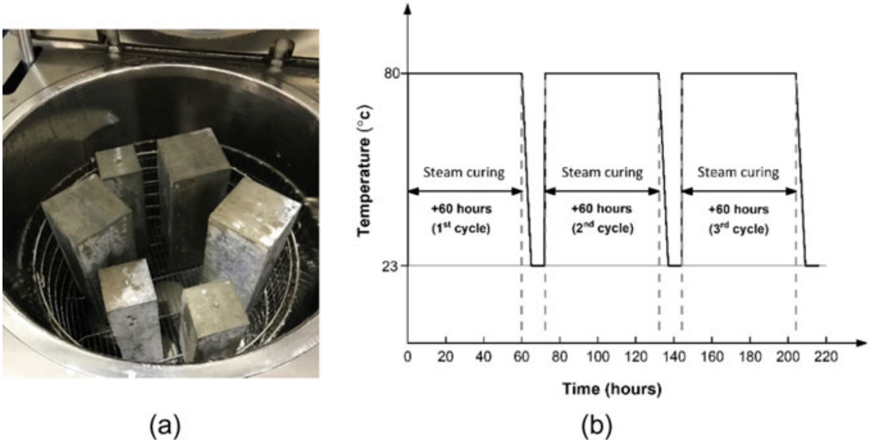

Fig. 2 Acceleration of the alkali–silica reaction (ASR) using the Zirbus LVSA 50/70 autoclave: **a** specimens in the autoclave and **b** time–temperature cycles for accelerating ASR

The inside the autoclave chamber was kept at atmospheric pressure. In total, three cycles of steam curing were applied, with 60 h of steam curing for each cycle. Figure 2a shows test specimens as placed in the autoclave, and Fig. 2b illustrates the temperature–time relationship of steam curing for the three cycles.

At the end of each cycle, the free expansion of the prisms, due to the accelerated ASR, was recorded and the next cycle was applied.

2.3 Expansion Measurements

Initial lengths of the prisms were measured and recorded using a digital comparator after demolding. After each cycle of steam curing in the autoclave, the prisms were taken out and stored in sealed plastic bags for 6 h to cool down to room temperature at 23 ± 2 °C, and then the length measurements were taken. Changes in length were used to calculate the expansion of the specimens after 1, 2, and 3 cycles of autoclave steam curing.

2.4 Mechanical Property Testing

At the age of 28 days, the modulus of elasticity and compressive strength were measured in accordance with AS1012.17 [8] and AS1012.9 [9] on ∅ 100 × 200 mm cylinders; at the end of each cycle, three cylinders were taken out of the autoclave and mechanical property tests were carried out.

2.5 Load Carrying Capacity Testing Under Four-Point Loading

For each batch, load carrying capacity tests were conducted on two reinforced beams at the age of 28 days under four-point loading; at the end of each cycle, one reinforced beam was taken out, cooled to room temperature, and tested for load carrying capacity. The remaining beam was kept for investigating long-term ASR effects on load carrying capacity. During the load capacity test, a real-time digital image correlation system (Mercury RT®) was used to carry out strain and in-plane displacement measurements.

3 Results and Discussion

3.1 Cracking of Specimens

Figure 3 shows the cracking pattern of the concrete cylinders and prisms after accelerated ASR. Typical external map cracking was observed on the surface of the specimens due to accelerated ASR expansion after three cycles of steam curing in the autoclave.

Fig. 3 External map cracking on cylinders and prisms after three cycles of steam curing in an autoclave

3.2 Expansion of Concrete Prisms

Figure 4 shows the length change of the concrete prisms from the time of demolding and after three cycles of steam curing in the autoclave. A slight shrinkage of approximately 0.019% was recorded during storage in the humidity cabinet up to the age of 28 days. Afterwards, due to accelerated ASR in the autoclave, the length of the prisms increased with each steam-curing cycle. The average expansion of the prisms was recorded as 0.05% after one cycle, 0.13% after two cycles and it reached about 0.18% after three cycles. According to ASTM C1778-20, aggregate having 1-year CPT expansion $\geq$ 0.12% and < 0.24% can be classified as highly reactive. For dacite aggregate, the 1-year CPT expansion result from Cement Concrete & Aggregates Australia is ≈0.23%. In the current study, using three cycles of steam curing, the expansion reached ≈0.18%. This result shortens the testing period for classifying aggregate reactivity. However, more cycles are needed for slowly reactive aggregate. Further study is suggested to test more aggregates ranging from nonreactive to very highly reactive to establish a standard testing procedure with fine-tuned parameters including temperature, duration, heating and cooling rates and number of cycles, to determine aggregate reactivity, following the ASTM C1778-20 expansion limit criterion.

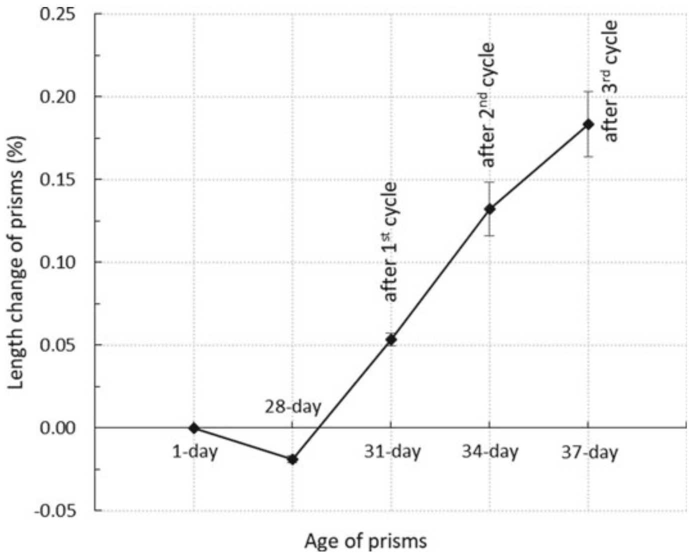

Fig. 4 Expansion of concrete prisms under three cycles of accelerated ASR in the autoclave

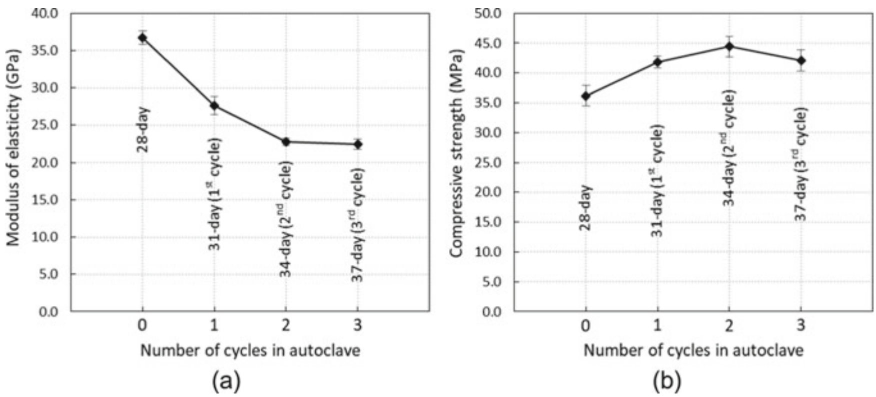

Fig. 5 Modulus of elasticity **a** and compressive strength **b** and before and after three cycles of steam curing in an autoclave

3.3 Mechanical Properties of Concrete Under Accelerated ASR Test Conditions

Figure 5a shows the modulus of elasticity test results at 28 days and after 1, 2, and 3 cycles of steam curing in the autoclave. It is generally acknowledged that the modulus of elasticity is the most sensitive mechanical property influenced by ASR. As can be seen, it decreased as expected with the ASR expansion achieved after each cycle of 80 °C steam curing using the autoclave. After the third cycle when average expansion reached 0.18%, a reduction of 39% was recorded in comparison with the initial 28-day value. The reduction was attributed to the microcracking of the concrete caused by accelerated ASR.

Figure 5b shows the compressive strength test results, which demonstrated that the compressive strength initially increased with increasing of number of cycles until the end of the second cycle, at a relatively low expansion level, and thereafter, the compressive strength showed a decreasing trend. With increasing expansion, compressive strength is expected to continue to decrease. This trend had been already observed by Gautam et al. [10]. They boosted the alkali content of concrete specimens to 1.25% Na_2O_{eq}. Samples were stored in hermetically sealed plastic pails and conditioned at 38 °C with RH > 95%. They reported that at age 365 days when ASR expansion reached 0.24–0.35%, the maximum reduction in compressive strength was 4–6%, in comparison with the 28-day compressive strength [10].

3.4 Load Carrying Capacity of Reinforced Concrete Beams

To investigate the reduction in load capacity of the reinforced concrete beams after accelerated ASR, load carrying capacity tests were conducted under four-point loading at the age of 28 days and after 1, 2, and 3 cycles of accelerated ASR. All the beams with 2 × N5 reinforcing steel bars failed in flexure and all the beams with 2 × N8 bars failed in shear. Figure 6 shows the initial load capacity of a typical reinforced concrete beam with 2 × N5 tested at the age of 28 days failing in flexure. Figure 7 demonstrates a reinforced concrete beam with 2 × N8 reinforcing bars tested after two cycles of accelerated ASR showing typical shear failure.

The load carrying capacity test results are shown in Fig. 8. It can be seen that, for the reinforced beams with 2 ×N5 bars, the flexural capacity was not significantly

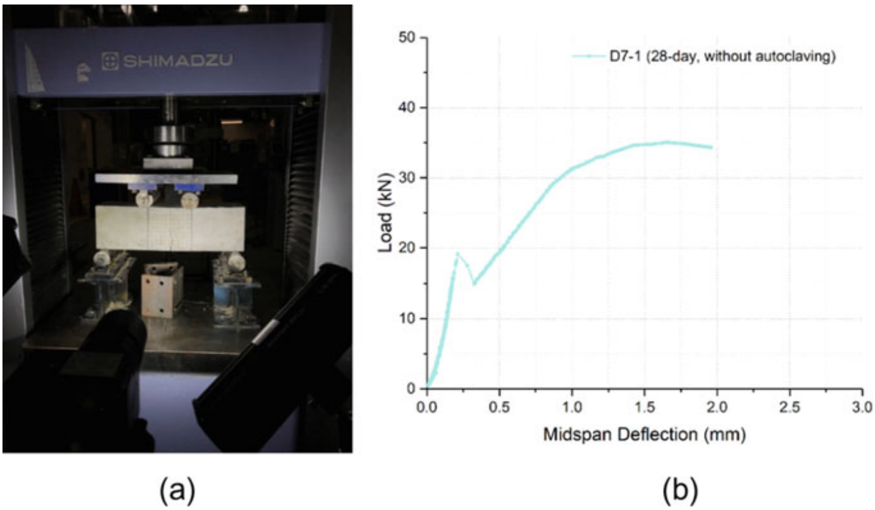

Fig. 6 Reinforced concrete beam with 2 × N5 bars tested at 28 days: **a** test set-up and **b** load–displacement curve

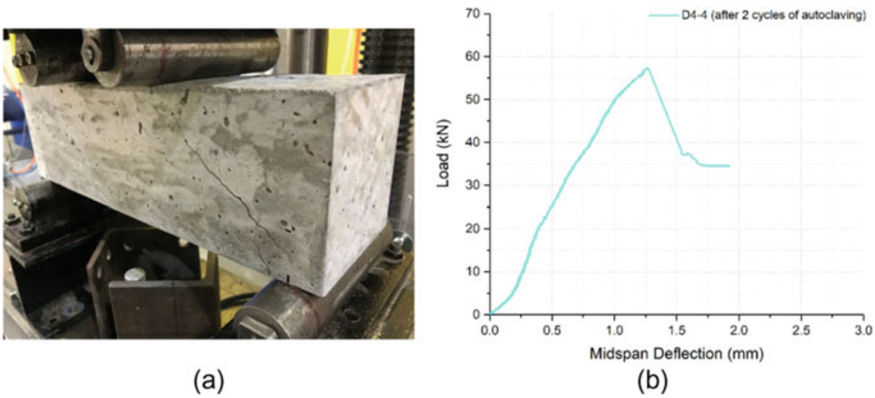

Fig. 7 Reinforced beam with 2 × N8 bars tested after two cycles of accelerated alkali–silica reaction: **a** failure mode and **b** load–displacement curve

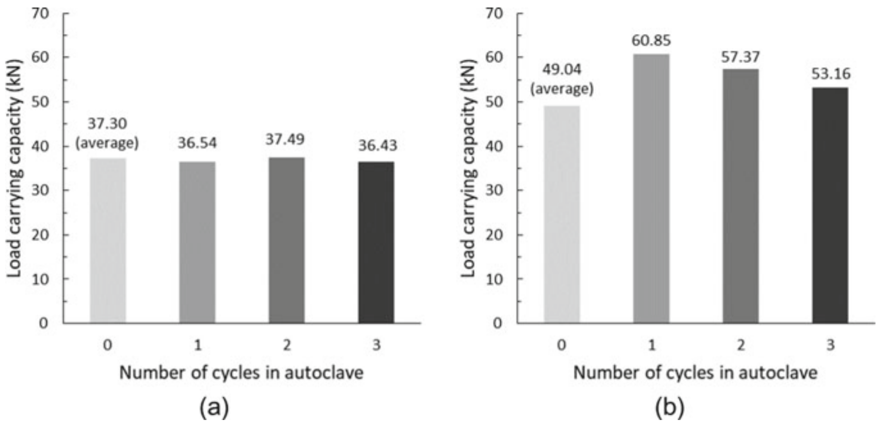

Fig. 8 Reinforced concrete beams with **a** 2 × N5 bars failed in flexure and **b** with 2 × N8 bars failed in shear

influenced by ASR expansion achieved under three cycles of accelerated test. Failure load of the reinforced beam with 2 × N8 bars was found increased after 1, 2, and 3 cycles of accelerated ASR in comparison with the 28-day value. This could be attributed to the prestressing effect of ASR expansion. Meanwhile, some reduction in the failure load after each cycle was recorded due to only one sample being tested for each cycle. Load carrying capacity at higher ASR expansion levels, however, needs further investigation.

4 Conclusions

(1) Using three cycles of 80 °C steam curing in an autoclave, the ultra-accelerated test produced ASR damage and expansion of alkali boosted concrete elements within 9 days.
(2) Modulus of elasticity systematically decreased with increasing number of 80 °C steam-curing cycles. Compressive strength increased until the end of the second cycle, and thereafter showed a decreasing trend.
(3) Shear resistance of reinforced beams with 2 × N8 bars was increased after 1, 2, and 3 cycles of accelerated ASR in comparison with the 28-day value. This could be attributed to the prestressing effect of ASR expansion.
(4) Flexural capacity of the beams reinforced with 2 × N5 bars was not significantly influenced by the extent of ASR expansion achieved in the current accelerated autoclave test.

Acknowledgements This research was funded through an Australian Research Council Research Hub for Nanoscience Based Construction Materials Manufacturing (IH150100006) with the support of Cement Concrete and Aggregates Australia.

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