Scientific paper

Time-dependent Effect of Expansion due to Alkali-silica Reaction on Mechanical properties of Concrete

Xi Ji1, Hyo Eun Joo1, Zhehui Yang2 and Yuya Takahashi3*

Received 30 December, accepted 11 June 2021  doi:10.3151/jact.19.714

Abstract

This study investigates the time-dependent mechanical properties of concrete deteriorated by the alkali–silica reaction (ASR). Previous analytical and experimental studies have indicated the positive impact of ASR gel in the cracks against mechanical damage in concrete. To study the effects of ASR gel on cracked concrete, groups of cylinder specimens with different expansion levels were prepared and tested at different material ages. The compression test results showed that the deteriorated elastic modulus of the specimens could be recovered over time. Mechanical property data from the other ASR studies were collected and assessed to observe similar trends across the literature. It was observed that the recovery of the elastic modulus also occurred in previously reported experiments. The recovery of the elastic modulus is assumed to be due to the time-dependent chemical and physical properties of ASR gel, which fills the cracks. Moreover, the data indicated that parameters other than material age and expansion could be attributed to the time-dependent mechanical properties of concrete affected by ASR.

1. Introduction

The alkali–silica reaction (ASR) is one of the most deleterious reactions in concrete, and its mechanism has been widely investigated for decades after Stanton et al. (1940) (e.g., Chatterji 1979; Mohammed et al. 2002; Copuroglu 2010). Many researchers have developed models to predict the ASR kinetics and expansion progress on concrete, which can be an efficient way to evaluate the effect of ASR on concrete performance (Multon et al. 2009; Morenon et al. 2017; Saouma 2014; Giorla et al. 2015; Kawabata and Yamada 2015; Charpin and Ehracher 2014; Pourbehi et al. 2019). However, the mechanism of microscopic ASR gel development and the effect of this development on the mechanical properties of concrete have not been elucidated till now.

The authors have previously conducted a study on the shear behavior of reinforced concrete (RC) beams affected by ASR using both analytical and experimental methods (Takahashi et al. 2014; Ogawa et al. 2018). In the analytical study by Takahashi et al. (2014), the stiffness and failure modes were compared for concrete beams with and without ASR. The study was conducted with the ASR model built on the basis of a multiscale analysis system (DuCOM-COM3, Maekawa et al. 2008), considering the thermodynamic equilibrium and solid-liquid two-phase interaction in the mechanical scheme (Takahashi et al. 2016). This model already succeeded in reproducing the anisotropic expansion and damage behaviors of uni-axial restraint ASR-affected specimens (Takahashi et al. 2015) and the RC slabs with multidirectional reinforcements with ASR expansion (Takahashi et al. 2018). The results of the simulated load-displacement relationships for RC beams with and without ASR from the previous study are shown in Fig. 1. It can be observed that the simulated beam with ASR shows lower stiffness than the beam without ASR, while the capacity of the beam with ASR is higher than that without ASR. It is also observed from the principal distribution of beams after a failure that the failure mode shifted from shearing failure to bending failure with ASR expansion for the specific dimensions of the RC beam in the study (Takahashi et al. 2014). The study to see the experimental trends was carried out by Ogawa et

---

1Ph.D student, Department of Civil Engineering, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, Japan.
2Master course student, Department of Civil Engineering, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku Tokyo, Japan.
3Assistant Professor, Department of Civil Engineering, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, Japan. *Corresponding author, E-mail: takahashi@concrete.t.u-tokyo.ac.jp
al. (2018). Three RC beam specimens were prepared with the same reactive coarse aggregate, and the load-deflection curves were compared under different temperature and pre-loading conditions (Fig. 2). This indicated that even if the stiffness of the RC beam was reduced by pre-loading, the decrease in stiffness was recovered by ASR up to the no ASR case level. Moreover, Ogawa et al. (2018) reported that the specimen without ASR resulted in shear failure, while the specimens with ASR showed bending failure; the failure mode shift was in agreement with the analytical study by Takahashi et al. (2014). From these analytical trials and experiments, it could be observed that ASR could improve the mechanical properties of RC members and change the failure mode in specific RC dimensions. It is assumed that multidirectional cracks induced by ASR can prevent shear crack progression and result in higher capacity.

The factors that affect the mechanical properties of concrete under ASR were investigated by many researchers. Giaccio et al. (2008) conducted an ASR experiment using aggregate with different reactivity and reported that the mechanical properties of concrete specimens are strongly affected by aggregate type, aggregate size, and reaction kinetics. Kongshaug et al. (2020) indicated with the experiment that ASR damage on stiffness decreases with smaller expansion as the expansion in a certain direction is strongly dependent on perpendicular microcracks. And uniaxial restraint could lead to higher stiffness because the measured expansion was smaller compared to specimens under free expansion. The confinement effect on mitigating damage by reducing crack-opening was also confirmed by Gautam et al. (2017b). Morenon et al. (2019) considered the positive role of ASR in flexural performance due to chemical prestress by ASR gel in reinforcement direction of RC beam, while authors experienced that stiffness of RC slab affected by ASR expansion cannot be explained only by chemical prestress force by ASR gel.

The authors assume that the additional strengthening effect for the observed stiffness recovery in the above paragraph could be caused by the time-dependent mechanical properties of ASR-affected concrete. In recent studies, time-dependent ASR characteristics have been investigated (Katayama 2012, Shi et al. 2019; Takahashi et al. 2020). This characteristic is of great importance for the accurate prediction of the long-term performance of concrete structures with ASR expansions. With the growth of material age, concrete affected by ASR could yield different mechanical performance (Gautam 2016). This phenomenon should be further validated on the basis of the material properties of cracked concrete, which can lead to a better understanding of the factors responsible for the maintenance of concrete structures deteriorated by ASR.

Based on this background, this study investigates the contribution of ASR expansion levels to the concrete mechanical properties at different material ages. An experiment with groups of cylinder specimens was designed in this study to determine the mechanical properties at different reaction stages. Moreover, experimental data from previous ASR studies on mechanical properties were collected to study the property changes induced by material age and expansion.

### 2. Materials and methods

As assumed in previous research (Ogawa et al. 2018), with the increase in reaction time, ASR gel could improve the mechanical properties of concrete by filling the cracks, and the composition of ASR gel could change over time. This time-dependent characteristic could cause the mechanical properties of concrete to vary at different material ages. Therefore, in this study, an experiment was designed to determine the mechanical properties of concrete specimens affected by ASR at different expansion levels and material ages.

Three groups of specimens in the form of $\phi 10 \times 20 \text{cm}$ cylinders were prepared with the mix proportions listed in Table 1. SP and AE in Table 1 denote the superplasticizer and air-entrained agent, respectively. Water-to-cement ratio was set to 65%, referring to the previous experiments (Ogawa et al. 2018, Maeshima et al. 2016). Reactive andesite was selected as the coarse aggregate, and additional NaOH was added to the mixing water to accelerate ASR. The three series of specimens were designed to keep no acceleration (N series), reach moderate expansion (M series, with around 2000 $\mu$ expansion), and high expansion (H series, with around 4000 $\mu$ expansion). After demolding, the contact chips were attached to the steel bands fixed on the specimens (Fig. 3), and the expansion measurement was conducted by

| Water | Cement | Sand | Gravel | SP | AE | NaOH |
|-------|--------|------|--------|----|----|------|
| 175   | 269    | 827  | 988    | 4.3| 0.011| 12.90|

Table 1 Mix proportion for concrete cylinders.

Fig. 2 Measured load-deflection curves of RC beams (Ogawa et al. 2018).
measuring the distance between the contact chips using a dial gauge. Table 2 shows the temperature and storage conditions of each series of specimens. Specimens in the N series were maintained at 20°C under sealing conditions during the entire test period. The specimens in series M and H were immersed in 3% NaCl solution at 40°C to accelerate ASR after sealed curing for 8 weeks and kept under acceleration conditions for 4 and 12 weeks, respectively. After acceleration, they were moved to be stored under the 20°C sealed condition. Here, NaCl solution is selected to have a correspondence with the environment of road structures in cold regions which suffer from de-icing salt. Each row in Table 2 represents the sequence of storage conditions for specimens in each group. At the material ages of 14, 26, 52, 78, and 104 weeks, corresponding specimens were taken to conduct compression tests. Compressometer (Fig. 4) connected with data logger was used to record the stress-strain relationship of specimens throughout the compression test. Three specimens were prepared under each experimental condition. The expansion history until corresponding material age and stress-strain curve under compression test were achieved for each specimen.

### Table 2 Series of specimens for compression test.

| Curing condition | Acceleration / Storage condition | Acceleration / Storage condition | Acceleration / Storage condition | Acceleration / Storage condition | Acceleration / Storage condition |
|------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| N                | 8w 20°C seal                     | 6w 20°C seal                     | 12w 20°C seal                   | 26w 20°C seal                   | 26w 20°C seal                   |
| M                | 8w 20°C seal                     | 4w 40°C 3% NaCl_iq → 2w 20°C seal | 12w 20°C seal                   | 26w 20°C seal                   | 26w 20°C seal                   |
| H                | 8w 20°C seal                     | 12 w 40°C 3% NaCl_iq → 6w 20°C seal | 26w 20°C seal                   | 26w 20°C seal                   | 26w 20°C seal                   |

*“o” means when compression test was conducted.*

3. Results and discussion

3.1 Expansion test results

Figure 5 shows the expansion progress of each specimen. As demonstrated by the results shown in Fig. 5, at weeks 14, 26, 52, 78, and 104, the expansion was recorded and shown with the legend denoting series and specimen number (ex. N-1 for No.1 specimen in series N). Even three specimens in the same series have different expansion progresses; therefore, each line for them is drawn separately in the figures. As for Fig. 5, It should be noted that specimens at different material ages represented by the same legend are different specimens. Under the acceleration and storage conditions considered for each series, specimens with different expansion levels can be obtained. Specimens in series N rarely had any expansion until week 52, while around 1000 μ occurred after week 78, which indicates that ASR still occurred when a low temperature (20°C) was constantly maintained. Contrastingly, the specimens in series M and H showed little expansion progress after they were kept in 20°C sealed storage after achieving around 2000 μ and 4000 μ expansion, respectively. This could be because the alkali and reactive silica were consumed to generate the ASR products in the M and H series specimens during the ASR acceleration period, while the N series specimens had more alkali and reactive silica under the 20°C storage conditions.
3.2 Compression test results

Figure 6 shows the stress–strain relationships determined through the compression tests, and Table 3 lists the expansion of specimens when expansion tests were conducted. The calculated compression strength and elastic modulus of specimens tested at different ages are as shown in Figs. 7 and 8. In the legends of the figures, the series (N, M, or H) and specimen numbers are given. The data for M-3 specimen at week 78 were missing because of the measurement failure during the compression test.

It could be indicated from the results that there was only a slight difference in peak strength among different series of specimens, and the peak strength for specimens in every series increased with material age. At the 14th week (Fig. 6(i)), the stiffness of the specimens in the M series was lower than that in the N series, which indicates the negative effect of ASR expansion on stiffness. Contrastingly, this difference in stiffness was reduced over time. At week 52 (Fig. 6(iii)), the stiffness of the N- and M-series specimens was almost the same. Moreover, at week 78 (Fig. 6(iv)), the stiffness of the M- and H-series specimens was higher than that of the N-series specimens. These results indicate that the damage caused during accelerated ASR stage was alleviated with increasing material age after stopping the ASR acceleration.

As observed from the expansion results in Figs. 5(iii) and 5(iv), approximately 1000 μ expansion occurs for the N-series specimens between weeks 52 and 78, and correspondingly, the stiffness of the N-series specimens decreased during this period. After week 78, slight expansion occurred in the N-series specimens, and their stiffness recovered from the 78th week to the 104th week. Although the expansion at weeks 52, 78 and 104 was not measured from the same specimens, the synchronous change of expansion and elastic modulus during this period could suggest that the mechanical properties damaged by ASR might be recovered with time.

3.3 Discussion

The measured modulus of elasticity and compression

|            | 14 weeks (μ) | 26 weeks (μ) | 52 weeks (μ) | 78 weeks (μ) | 104 weeks (μ) |
|------------|--------------|--------------|--------------|--------------|---------------|
| N-1        | 60           | -44          | -204         | 1559         | 852           |
| N-2        | 10           | 126          | -197         | 603          | 1385          |
| N-3        | 25           | 10           | -20          | 919          | 543           |
| M-1        | 293          | 1685         | 1597         | 1394         | 1609          |
| M-2        | 2201         | 3261         | 701          | 2668         | 2255          |
| M-3        | 1831         | 2465         | 1824         | -            | 1673          |
| H-1        | 5291         | 4235         | 5143         | 3412         |
| H-2        | 4623         | 3531         | 3625         | 3265         |
| H-3        | 4292         | 2127         | 3590         | 3274         |

Table 3 The expansion of specimens when conducting compression tests.

Fig. 5 Expansion progress of specimens at different material ages.
strengths were plotted against expansion for the specimens with the same material age in Figs. 9 and 10, respectively. From Fig. 9, it can be observed that with larger expansion, the modulus of elasticity is typically lower. While the reduction of the modulus of elasticity with the increase in expansion was evident at the younger material age (Fig. 9(i)), the slope of the graph decreases when the material age increases. Finally, almost no decrease in stiffness can be observed when comparing the specimens with expansion of ~4000.
Therefore, it appears that the stiffness of specimens damaged by ASR could recover over time. The modulus of elasticity of the N-series specimens decreased at week 78 (Fig. 9(iv)) compared to that before week 78, probably because of the expansion that occurred between weeks 52 and 78. However, the modulus of elasticity of the N-series specimen recovered over weeks 78–104, which could be attributed to the time-dependent recovery of stiffness in ASR.

At week 104 (Fig. 9(v)), three specimens in the H series yielded similar expansion strains (3412, 3265, and 3274 μ for H-1, H-2, and H-3, respectively). However, their moduli of elasticity varied largely (18.7, 23.1, and 13.4 GPa for H-1, H-2, and H-3, respectively), which implies that except expansion and material age, other dominant factors could affect the mechanical properties in the case of concrete affected by ASR. For instance, different three-dimensional crack distributions could result in variations in the mechanical properties. In the fatigue experiment of real-scale RC slabs by Maeshima et al. (2016), it was found that the mechanical properties were more largely deteriorated in a specimen with an extensive penetrating crack compared to those in the specimens with distributed cracks, considering both specimens bear a similar amount of expansion. The distribution of cracks could affect the small-scale specimens in the same way as the effect observed for real-scale RC slabs, and this effect should be further studied in the future to facilitate the investigation of concrete structures deteriorated by ASR.

In Fig. 10, although the compression strength decreased slightly with larger expansion at each material age, the indicated trend was not evident in this study. For the specimens in the three series, the compression strength progressively increased with time, which could be attributed to gradual hydration. For the N-series specimens from weeks 78 to 104, the compression strength decreased slightly, while the stiffness recovered to a higher level. Therefore, gradual hydration under 20°C under the sealed condition is not the cause of stiffness recovery over time in this ASR experiment.

The deteriorated modulus of elasticity was recovered with the progressing of material age in ASR-affected concrete. Figure 11 shows the relationships between the elastic modulus and expansion measured in the experiment at 14, 26, 52, and 104 weeks. The trends of the deteriorated modulus of elasticity with expansion can be observed. The modulus of elasticity recovery phenomenon is assumed to be attributed to the filling of the cracks by ASR gel with time progression, as illustrated in Fig. 12. Immediately after the penetration of cracks into the cement paste, less ASR gel is filled in the cracks,
and the cracks can harm the mechanical properties of concrete. However, with time, ASR gel can migrate into the cracks and withstand the external stress, and also the chemical compositions and physical properties of ASR gel can change; thus, the mechanical properties of concrete can be recovered with time after ASR expansion. As shown in Fig. 12(iii), the chemical composition of ASR could also change with time. For example, the calcium ion in cement paste could exchange with the sodium or potassium ion in ASR gel, which could result in different local mechanical properties. However, the solidification of ASR gel with calcium ion may not be enough to explain the full recovery of elastic modulus in this experiment as such exchange of ions normally only happens at the interface of cement paste and aggregate. Other possible mechanisms should be explored in future research to confirm the stiffness recovery phenomenon.

4. Relationship between mechanical properties and expansion reported by previous studies

As pointed out by previous research works (Giaccio et al. 2008; Leemann et al. 2021), the degree of reduction of mechanical parameters with the increase of ASR expansions can have a wide variation due to the mineralogy of the rock, the size of the aggregate, the reaction kinetics, etc., because of the different progresses in macro- and micro-cracks. And most of the previous discussions treated the reductions as “progressing” deterioration, and little research mentioned the possibility of the recovery of the mechanical properties (Gautam 2016).

In this section, the previously reported measurement data on the mechanical properties of concrete after ASR are collected (Giaccio et al. 2008, 2015; Kagimoto et al. 2014; Ahmed et al. 2003; Swamy et al. 1998; Gautam et al. 2017a, 2017b; Liao et al. 2020; Esposito et al. 2016; Abd-Elssamd et al. 2020) to verify the trend observed in the previous section and discuss whether the progressing of material age can have a positive effect on the mechanical properties (Gautam 2016). Table 4 lists the previously reported experimental details. As indicated in Table 4, the experimental conditions, which affect the intensity of ASR, vary among experimental groups in cases (i) to (vii).

Specifically, the type, amount, or distribution of the aggregate were considered as variates in cases (i)–(v) and (vii), and different curing conditions were applied to the specimens in case (vi). In cases (viii) and (ix), specimens were divided into groups according to the confinement level. In case (x), additional material (fiber) was added into the mix proportion. They appeared to yield different expansion amounts, expansion rates, and mechanical property results on the basis of the material and ASR accelerating method they adopted. The data from these studies are rearranged according to the material age, as focused in this study.

First, the expansion progress of each study is listed, as shown in Fig. 13. As the material varies significantly among these experiments, the expansion curves show different reaction intensities. For example, the expansion of “Mix A” specimens in Fig. 13(iii) was more than 2% at week 40, while the maximum expansion was lower than 0.4% until week 120 in Fig. 13(i). Additionally, according to the slope of the expansion curve, the expansion of specimens could have been terminated (e.g., Fig. 13(i)) or were still under rapid development (Fig. 13(vi)) depending on the experiment. The material ages at which the mechanical property results were extracted are marked with gray dashed lines in Fig. 13, and the obtained modulus of elasticity and compression strength are plotted against expansion by grouping the same material age. The discussion is focused on mechanical property changes with material age and possible factors that could result in changes according to these studies.

4.1 Relationship between elastic modulus and expansion

Figure 14 shows the relationship between the elastic modulus and expansion in the experiments. We can confirm from Fig. 14 that the different relationship between elastic modulus reductions and expansions can be obtained with each experimental set up as discussed in the previous research works (Giaccio et al. 2008; Leemann et al. 2021). And in Fig. 14, different extents of stiffness recovery (marked by guidelines) can be observed, except in Fig. 14(vi). The rate of reduction of the elastic modulus with the increase in expansion decreased when the material age increased.
Table 4 Experimental conditions applied in previous studies.

| Specimens shape | Materials | ASR acceleration method |
|-----------------|-----------|-------------------------|
| Variable        | W/C       | Na₂Oeq (kg/m³)          | aggregate                              |
|                  |           |                        |                                        |
| **(i) Giaccio et al. 2008** | Reactive aggregate amount | Reactive siliceous orthoquartzite, reactive/non-reactive granite and sand | Wet sealed curing in 38°C |
| 75×75×300 mm prism | 0.42 | 5.25 |                                        |
| 100×200 mm cylinder | 150×300 mm cylinder |                                        |
| **(ii) Kagimoto et al. 2014** | Mix proportion addition alkali amount | Reactive fine and coarse aggregate | Moist sealed curing in 40°C |
| 100×100×400 mm prism | 0.55 | 5.3-11.2 |                                        |
| unknown          | 100 mm cube |                                        |
| **(iii) Ahmed et al. 2003** | Reactive aggregate | Fused silica, thanes valley sand | Immersed in 38°C water |
| 100×100×500 mm prism | 100 mm cube | 0.5 | 7 |                                        |
| 150×300 mm cylinders |                                        |
| 100 mm cube |                                        |
| **(iv) Swamy et al. 1988** | Aggregate type | Beltane opal amorphous fused silica | Moist storage storing in 20°C |
| 75×75×300 mm prism | 0.44 | 5.2 |                                        |
| 100 mm cube |                                        |
| 100×100×500 mm prism |                                        |
| **(v) Gautam et al. 2017a** | Coarse aggregate distribution | Spratt aggregate | Moist sealed curing in 38°C |
| 75×75×285 mm prism | 0.44 | 5.25 |                                        |
| 100×200 mm cylinder |                                        |
| **(vi) Liao et al. 2020** | Curing solution | Reactive fine aggregate | Moist curing in 20°C → immersed in NaOH/NaCl solutions |
| 25×25×285 mm prism | 0.45 | 6.08 |                                        |
| 40×40×160 mm prism |                                        |
| 50×100 mm prism |                                        |
| **(vii) Esposito et al. 2016** | Aggregate | Dutch and Norwegian aggregate | Moist curing in 38°C |
| 75×75×280 mm prism | 0.46 | 4.45 |                                        |
| 100×100×400 mm prism |                                        |
| **(viii) Gautam et al. 2017b** | Confinement | Spratt aggregate | Wet sealed curing in 23°C for six months → moist curing in 50°C |
| 254 mm cube | 0.44 | 5.25 |                                        |
| 75×150 mm core drilled from cube specimens |                                        |
| **(ix) Abd-Elssamd et al. 2020** | 1. Confinement 2. aggregate reactivity | Reactive lime stone, non-reactive natural sand | Moist storage in 38°C after 28 days |
| 76.2×76.2×79.4 mm prism | 0.5 | 6.3 |                                        |
| 100×200 mm cylinder |                                        |
| **(x) Giaccio et al. 2015** | Additional material (fiber) | Coarse aggregate with 40% highly reactive crushed stone | Wet sealed curing in 20°C |
| 75×105×430 mm | 0.42 | 2.8/4.0 |                                        |
| 100×200 mm cylinders |                                        |
| 150×300 mm cylinders |                                        |
Fig. 13 Expansion progress of specimens in previous experiments.

Note. Meaning of legends:

Fig. (ii): “mix proportion—alkali amount”
Ex. “CA-3.6” means mix proportion CA designed in Kagimoto et al. 2014 with alkali contents of 3.6 kg/m³

Fig. (v): “solution”
Ex. “5% NaCl” means the specimens were kept in 5% NaCl solution
Fig. (vii): “RR1”: mix design with Dutch aggregate; “RR2”: mix design with Norwegian aggregate

Fig. (viii): “stress state”
Ex. “Uni-axial(3.9,0,0)” means the specimens was under uni-axial confinement with the confinement strength to be 3.9 MPa, 0, 0 on each direction

Fig. (x): “fiber type: alkali amount(1.28 kg/m³, 2.40 kg/m³)”
Ex. “no-fiber_2” means no fiber is added into the mix proportion and the total alkali amount is 2.40 kg/m³.
Fig. 14 Relationships between elastic modulus and expansion in previous experiments.
The elastic modulus recovery capacity is related to the expansion amount. Roughly speaking, it can be observed that the stiffness recovery phenomenon is more evident when the expansion is below around 5000 \( \mu \) than that when the expansion above around 5000 \( \mu \). (In Fig. 14, the red dashed lines are plotted at 5000 \( \mu \) expansion to separate the expansion range) In Section 3, full recovery of elastic modulus happened to the specimens, and this may also be attributed to that the expansion of specimens was under 5000 \( \mu \). The proposed mechanism for the stiffness recovery could also explain this phenomenon. When the expansion is small, the generated ASR gel can fill the cracks, whereas when the crack width increases with expansion, the volume of ASR gel might not be enough to fill the enlarged cracking space. And large expansion could greatly reduce the safety of the concrete structure. Therefore, stiffness recovery should only be considered when ASR has not caused obvious damage to concrete structures in maintenance, and crack-filling repairment should also be conducted to prevent other durability problems. It should be noted that the value of 5000 \( \mu \) can be reconsidered based on the detailed research about the recovery mechanisms in future.

The elastic modulus recovery is related to the ASR stage and rate. In Fig. 14(vi), the reduction in the elastic modulus with the expansion is even accelerated when the material age increases, and it is the same for compression strength explained in the following section. One possible reason for the lack of signs of elastic modulus recovery and deterioration of mechanical properties in this case could be that ASR is still in the early stage until the end of the measurement. The expansion tends to occur rapidly as ASR is initiated and then slows down after a certain period. Finally, the expansion curve reached a plateau when the reactants were almost consumed. However, in Fig. 13(vi), the expansion curve is almost linear, which indicates that the reaction is still in the early stage. Continuous expansion could increase the damage rate. Therefore, the filling effect of ASR gel is less dominant than the recovery of the mechanical properties. In Fig. 14(viii), the elastic modulus tends to recover after 39 weeks, and accordingly, the expansion slows down and approaches the plateau simultaneously. This is the same for the case in Section 3, where the elastic modulus recovery is clear after manually stopping ASR. In Giaccio et al. (2015), the specimens were divided into two groups with different alkali amounts. The expansion curve indicates that the expansion of Group 2 specimens (4.0 kg/m\(^3\) of alkali in mix proportion) was almost terminated at approximately 16th week, while the Group 1 specimens (2.8 kg/m\(^3\) of alkali in mix proportion) continued to expand. The results of these groups are replotted in Fig. 15. It could be observed that the elastic modulus keeps deteriorating in Group 1, while that in Group 2 slightly increases with the time and expansion growth. Therefore, the Group 2 specimens yield a more evident elastic modulus recovery than the Group 1 specimens. As a result, the mechanical properties could be improved owing to the slowly progressing reaction. The comparison in this section is only conducted with the laboratory experiments, not with the real structures. Generally, it is reported that the elastic modulus of cores picked from real structures decreases comparing to sound concrete (Rivard et al. 2010; Barbosa et al. 2018). So, the applicability of this idea for filed concrete should be further studied in future, but the reaction rate dependence can facilitate the strategy of maintenance of field concrete affected by ASR. At ambient temperature and relative humidity, the field concrete will expand much slowly compared to that in the accelerated experiments conducted in the laboratory. Therefore, concerning ASR deterioration, if the stiffness of the slowly reacted concrete within a certain level of expansion could be recovered, maintenance of the concrete structures could be conducted by cutting the water supply and allowing the stiffness to recover itself.

Katayama (2012) reported that the calcium-to-silica ratio (Ca/Si) of ASR gel increases with time and that ASR gel could migrate from aggregate to cement paste. Additionally, the authors previously studied the relationship between chemical compositions and micro-
scopic stiffness of ASR gel (Okano and Takahashi 2021) on the basis of experimental results in the literature (Zheng et al. 2016; Hu et al. 2018; Leemann et al. 2018). Figure 16 presents the Young’s modulus measured by micro/nanoindentation measurement techniques and Ca/Si obtained by scanning electron microscopy energy dispersive X-ray spectrometry (SEM-EDS). Figure 16 demonstrates a distinct increasing trend in the elastic modulus of ASR gel—from the order of a few to tens of gigapascals—with an increase in the Ca/Si ratio. Such variations in the chemical components and mechanical properties of ASR gel could account for the time-dependent mechanical properties mentioned above. Contrastingly, the volume ratio of ASR gel to concrete is less than a few percent; thus, it is not completely clear whether the stiffness development of ASR gel could account for the elastic modulus recovery in concrete affected by ASR. The viscosity change under accelerated ASR condition was observed by previous researchers (e.g., Kawabata et al. 2019). As high alkali amount and high temperature were applied to accelerate ASR in experiments in Section 2, low viscosity may lead to easier flowing out of ASR gel from aggregate to cement paste. Thus, more solidification of ASR gel and recovery of stiffness happened. Therefore, other factors such as density or viscosity could also lead to a time-dependent change in the elastic modulus, which should be further studied, based on the microscopic observations and characterizations of ASR gel, such as being studied recently by Geng et al. (2020a, 2020b). Moreover, the resistance of ASR gel inside cracks against tension and shear forces must be further analyzed to understand the microscopic concrete behavior and improve models predicting the performance of concrete structures expanded by ASR.

Confinement could potentially improve the stiffness recovery progress. In Fig. 14(viii), the elastic modulus decreased first from week 9 to week 39 and then recovered until the end of test duration (week 78). In the experiment by Gautam et al. (2017b), a significantly high compression force (3.9 MPa, 9.6 MPa) was applied to confine the expansion of the specimens. While fiber can also reduce the crack width as an external confinement, the stiffness recovery is not as obvious as that in Fig. 14(x). The stress generated by the fiber to close the cracks is considerably lower than that induced by external forces such as the one applied in Gautam et al. (2017b). Contrastingly, fiber could also reduce the number of cracks, which has already slowed the deterioration in stiffness by ASR damage in the expanding procedure. Therefore, the crack filling effect by ASR gel was not apparent in the late stage.

4.2 Relationship between compression strength and expansion

Figure 17 shows the relationship between compression strength and expansion. The overall compression strength in the collected literature appears to be less affected by ASR damage because the compression strength was not as obviously reduced as that in the elastic modulus with the progressing expansion. In Figs. 17(ii) and 17(v), the compression strength generally remains at the same level as the beginning stage for the entire reaction progress. In other cases, it is shown that the compression strength could increase with expansion and material age, especially at the initial stage. In Gautam et al. (2017b) (Fig. 17(viii)), the compression strength continued to increase, which could be attributed to the damage mitigation by external confinement. The
relationship between compression strength and expansion indicated in Fig. 17 is generally in agreement with what is shown in Fig. 10, where the gradual hydration may improve the compression strength during the progressing period of ASR. Additionally, the compression strength is not as distinctly deteriorated by ASR as the elastic modulus. However, the hydration effect could also be encountered by ASR damage when the specimens are expanded rapidly by ASR (Figs. 17(vi), 17(ix), and 17(x)). Unlike the elastic modulus recovery, which occurs at the late stage of the experimental duration, the compression strength increment tends to occur at the

Fig. 17 Relationships between compressive strength and expansion in previous experiments.
beginning stage. Therefore, while the mechanism of the elastic modulus recovery is assumed to be due to the crack filling effect by ASR gel, that of the increment of compression strength should be different.

5. Conclusion

This study investigated the changes in the mechanical properties of concrete along with the progression of ASR. Groups of cylinder specimens with different expansions were prepared, and their mechanical properties at different material ages were recorded. It was confirmed that the stiffness of concrete can be recovered as the material age increases. Moreover, the mechanical property data from previous studies on ASR-affected concrete were collected and assessed to verify the time-dependent mechanical properties phenomenon. This characteristic of stiffness recovery has the potential to facilitate the maintenance of concrete structures deteriorated by ASR in the future. Based on the analytical and experimental results, the following conclusions are derived:

(1) According to the experiment results of cylinder specimens, the damage to the elastic modulus of concrete caused by ASR could be recovered over time after stopping the expansion of ASR. The time-dependent chemical and physical properties of ASR gel are assumed to be one of the reasons that contribute to the stiffness recovery.

(2) According to data analysis conducting on previous research works of ASR-affected mechanical properties, it was observed that stiffness recovery also occurs when the expansion is within a specific range.

(3) Other parameters such as confinement and the existence of fiber can also affect the time-dependent mechanical performance largely. The parameters affecting stiffness recovery and the applicable range of this phenomenon should be further analyzed in order to facilitate concrete structure maintenance in practice.

Acknowledgments

This study was financially supported by JSPS KAKENHI Grant No. 18H01507. And this paper is an extended and enhanced version of the work originally titled ‘Contribution of Alkali-Silica Reaction Gel on Time-Dependent Mechanical Properties of Concrete’ reported in “Advances in Construction Materials Proceedings of the ConMat’20”, which is edited as the proceeding of Sixth International Conference on Construction Materials (ConMat’20).

References

Abd-Elssamd, A., Ma, Z. J., Le Pape, Y., Hayes, N. W. and Guimaraes, M., (2020). “Effect of alkali-silica reaction expansion rate and confinement on concrete degradation.” ACI Materials Journal, 117(1), 265-277.

Ahmed, T., Burley, E., Rigden, S. and Abu-Tair, A. I. (2003). “The effect of alkali reactivity on the mechanical properties of concrete.” Construction and Building Materials, 17(2), 123-144.

Barbosa, R. A., Hansen, S. G., Hansen, K. K., Hoang, L. C. and Gre U., (2018). “Influence of alkali-silica reaction and crack orientation on the uniaxial compressive strength of concrete cores from slab bridges.” Construction and Building Materials, 176, 440-451.

Charpin, L. and Ehrlacher, A., (2014). “Simplified model for the transport of alkali-silica reaction gel in concrete porosity.” Journal of Advanced Concrete Technology, 12, 1-6.

Chatterji, S., (1979). “The role of Ca(OH)2 in the breakdown of Portland cement concrete due to alkali-silica reaction.” Cement and Concrete Research, 9(2), 185-188.

Curoguolu, O., (2010). “Effect of silica dissolution on the mechanical characteristics of alkali-reactive aggregates.” Journal of Advanced Concrete Technology, 8(1), 5-14.

Esposito, R., Ana, C., Hendriks, M. A. and Curoguolu, O., (2016). “Influence of the alkali-silica reaction on the mechanical degradation of concrete.” Journal of Materials in Civil Engineering, 28(6), 04016007.

Gautam, B. P., (2016). “Multiaxially loaded concrete undergoing alkali-silica reaction (ASR).” Thesis (PhD). University of Toronto.

Gautam, B. P., Panesar, D. K., Sheikh, S. A. and Vecchio, F. J., (2017a). “Effect of coarse aggregate grading on the ASR expansion and damage of concrete.” Cement and Concrete Research, 95, 75-83.

Gautam, B. P., Panesar, D. K., Sheikh, S. A. and Vecchio, F. J., (2017b). “Effect of multiaxial stresses on alkali-silica reaction damage of concrete.” ACI Materials Journal, 114(4), 595-604.

Geng, G., Shi, Z., Leemann, A., Borca, C., Huthwelker, T., Glazyrin, K., Pekov, I. V., Churakov, S., Lothenbach, B., Dähn, R. and Wieland, E., (2020a), “Atomic structure of alkali-silica reaction products refined from X-ray diffraction and micro X-ray absorption data.” Cement and Concrete Research, 129, 105958.

Geng, G., Shi, Z., Leemann, A., Glazyrin, K., Kleppe, A., Daisenberger, D., Churakov, S., Lothenbach, B., Wieland, E. and Dähn, R., (2020b). “Mechanical behavior and phase change of alkali-silica reaction products under hydrostatic compression.” Acta Crystallographica Section B: Structural Science, Crystal Engineering and Materials, 76(4), 674-682.

Giaccio, G., Zerbino, R., Ponce, J. M. and Batic, O. R., (2008). “Mechanical behavior of concretes damaged by alkali-silica reaction.” Cement and Concrete Research, 38(7), 993-1004.

Giaccio, G., Bossio, M. E., Torrijos, M. C. and Zerbino, R., (2015). “Contribution of fiber reinforcement in concrete affected by alkali-silica reaction.” Cement
and Concrete Research, 67, 310-317.
Giorla, A., Scrivener, K. and Dunant, C., (2015). “Influence of visco-elasticity on the stress development induced by alkali-silica reaction.” Cement and Concrete Research, 70, 1-8.
Hu, C., Gautam, B. P. and Panesar, D. K., (2018). “Nano-mechanical properties of alkali-silica reaction (ASR) products in concrete measured by nano-indentation.” Construction and Building Materials, 158, 75-83.
Kagimoto, H., Yasuda, Y. and Kawamura, M., (2014). “ASR expansion, expansive pressure and cracking in concrete prisms under various degrees of restraint.” Cement and concrete research, 59, 1-15.
Katayama, T., (2012). “ASR gels and their crystalline phases in concrete - Universal products in alkali-silica, alkali-silicate and alkali-carbonate reactions.” In: Proceedings of 14th International Conference on Alkali Aggregate Reaction, paper 030411-KATA-03.
Kawabata, Y. and Yamada, K., (2015). “Evaluation of alkalinity of pore solution based on the phase composition of cement hydrates with supplementary cementitious materials and its relation to suppressing ASR expansion.” Journal of Advanced Concrete Technology, 13(11), 538-553.
Kawabata, Y., Dunant, C., Yamada, K. and Scrivener, K., (2019). “Impact of temperature on expansive behavior of concrete with a highly reactive andesite due to the alkali-silica reaction.” Cement and Concrete Research, 125, 105888.
Kongshaug, S. S., Oseland, O., Kanstad, T., Hendriks, M. A., Rodum, E. and Markeset, G., (2020). “Experimental investigation of ASR-affected concrete-The influence of uniaxial loading on the evolution of mechanical properties, expansion and damage indices.” Construction and Building Materials, 245, 118384.
Leemann, A. and Lura, P., (2013). “E-modulus of the alkali-silica-reaction product determined by micro-indentation.” Construction and Building Materials, 44, 221-227.
Leemann, A., Menéndez, E. and Sanchez, L., (2021). “Assessment of damage and expansion.” RILEM State-of-the-Art Reports, 31, 491-498.
Liao, Y., Deng, Z., Ma, J., Zhang, Y., Shen, C. and Chen, D., (2020). “Effect of anions on behavior of mortar exposed to alkali-silica reaction.” Construction and Building Materials, 252, 119117.
Maekawa, K., Ishida, T. and Kishi, T., (2008). “Multiscale modeling of structural concrete.” London: CRC Press.
Maeshima, T., Koda, Y., Iwaki, I., Naito, H., Kishira, R. Suzuki, Y., Ohta, K. and Suzuki, M., (2016). “Influence of alkali silica reaction on fatigue resistance of RC bridge deck.” Journal of JSCE, 72(2), 126-145.
Mohammed, T. U., Hamada, H. and Yamaji, T., (2003). “Relation between strain on surface and strain over embedded steel bars in ASR affected concrete members.” Journal of Advanced Concrete Technology, 1, 76-88
Morenon, P., Multon, S., Sellier, A., Grimal, E., Hamon, F. and Boudarot, E., (2017). “Impact of stresses and restraints on ASR expansion.” Construction and Building Materials, 140, 58-74.
Morenon, P., Multon, S., Sellier, A., Grimal, E., Hamon, F. and Kollmayer, P., (2019). “Flexural performance of reinforced concrete beams damaged by alkali-silica reaction.” Cement and Concrete Composites, 104, 103412.
Multon, S., Sellier, A. and Cyr, M., (2009). “Chemomechanical modeling for prediction of alkali silica reaction (ASR) expansion.” Cement and Concrete Research, 39, 490-500.
Ogawa S., Takahashi, Y. and Maekawa, K., (2018). “The effect of preceding bending cracks of ASR affected reinforced concrete beams on their expansion and mechanical behaviors.” Proceedings of the Japan Concrete Institute, 40(1), 867-872.
Okano, Y. and Takahashi, Y., (2021). “Macroscale and microscale studies on time-dependent mechanical properties of concrete with alkali silica reactions.” Lecture Notes in Civil Engineering, 101, 1881-1890.
Pourbehi, M. S. and van Zijl, G. P., (2019). “Seismic analysis of the Kleinplaas Dam affected by alkali-silica reaction using a chemo-thermo-mechanical finite element numerical model considering fluid structure interaction.” Journal of Advanced Concrete Technology, 17(8), 462-473.
Rivard, P., Ballivy, G., Gravel, C. and Saint-Pierre, F., (2010). “Monitoring of an hydraulic structure affected by ASR: A case study.” Cement and Concrete Research, 40(4), 676-680.
Saouma, V. E., (2014). “Numerical Modeling of AAR.” London: CRC Press.
Shi, Z., Geng, G., Leemann, A. and Lothenbach, B., (2019). “Synthesis, characterization, and water uptake property of alkali-silica reaction products.” Cement and Concrete Research, 121, 58-71.
Stanton, T. E., (1940). “Expansion of concrete through reaction between cement and aggregate.” Proceedings of the American Society of Civil Engineers, 66(10), 1781-1812.
Swamy, R. N. and Al-Asali, M. M., (1988). “Engineering properties of concrete affected by alkali-silica reaction.” Materials Journal, 85(5), 367-374.
Takahashi, Y., Shibata, K., and Maekawa, K. (2014). “Chemo-hygral modeling and structural behaviors of reinforced concrete damaged by alkali silica reaction.” In: Proceedings of Asian Concrete Federation-2014, 1274-1281.
Takahashi, Y., Shibata, K., Maruno, M. and Maekawa, K., (2015). “Uniaxial restraint tests under high stress condition and a chemo-hygral model for ASR expansion.” In: C. Hellwich, J. Kolleger, B. Pichler, Proceedings of CONCREEP 10, Mechanics and Physics of Creep, Shrinkage and Durability of
Takahashi, Y., Ogawa, S., Tanaka, Y. and Maekawa, K., (2016). “Scale-dependent ASR expansion of concrete and its prediction coupled with silica gel generation and migration.” *Journal of Advanced Concrete Technology*, 14(8), 444-463.

Takahashi, Y., Ogawa, S., Tanaka, Y. and Maekawa, K., (2018) “Nonlinear coupling models of alkali-silica reaction and multi-directional cracked reinforced concrete.” In: *Proceedings of the Conference on Computational Modelling of Concrete and Concrete Structures* (EURO-C 2018), 353-362

Takahashi, Y., Okano, Y. and Yang Z., (2020). “Contribution of alkali-silica reaction gel on time-dependent mechanical properties of concrete.” In: *Proceedings of the Conmat’20*, No.7-3-6.

Zheng, K., Lukovic, M., de Schutter, G., Ye, G and Taerwe, L., (2016). “Elastic modulus of the alkali-silica reaction rim in a simplified calcium-alkali-silicate system determined by nanoindentation.” *Materials*, 9(9), 787.