Restraint Effect of Reinforcing Bar on ASR Expansion and Deterioration Characteristic of the Bond Behavior

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Abstract
To investigate the restraint effect of reinforcing bar on the expansion induced by alkali-silica reaction (ASR), and assess the mechanical behavior of reinforced concrete (RC) structure damaged by ASR, pullout tests of specimens with different ASR expansion were conducted. Accelerated ASR tests of specimens with diameters of 12 mm, 16 mm, and 20 mm were conducted to qualify the restraint effect of reinforcing bar. Pullout tests were used to investigate the relationship between nominal bond strength and ASR expansion. Test results show that ASR expansion decreases with the increase of the rebar diameter. Nominal bond strength of specimens increased initially to attain their peak at 14 days, approximately with the expansion of 0.035%. After that, the nominal bond strength decreased near-linearly with the increment of the expansion. A simplified ASR expansion model integrated with the poro-mechanical model was adopted to analyze the restraint effect. The verification of the proposed method was conducted by comparing the analytically predicted results with the test data. The results show that the proposed method could accurately predict both the ASR expansion and bond strength.

1. Introduction
Alkali-Silica Reaction (ASR) is a complex chemical reaction between alkalis in the pore solution of concrete and reactive silica in aggregates, which causes expansions and cracks of concrete (Swamy 2002). The strength and stiffness of concrete will be significantly affected by ASR and it is regarded as one of the most critical causes of deterioration of reinforced concrete (RC) structures, such as bridges and dams (Sargolzahi et al. 2010; Reinhardt et al. 2018; Taghvayi et al. 2018). The mechanism (Rajabipour et al. 2015; Liaudat et al. 2019), influence factors (Yang et al. 2018; Multon et al. 2010; Multon and Toutlemonde 2010), and the mitigation methods (Shehata and Thomas 2000; Ye and Chen 2019) of ASR were widely studied by many researchers.

At the RC structural level, it was noticed that the stress state has a significant effect on the expansions and cracks caused by ASR (Liaudat et al. 2018). The stress could be due to the internal restriction by reinforcing bars or the external restriction by boundary conditions. Numerous test programs have been conducted to study the mechanical restraint effect on ASR expansion by providing sustained or variable compressive stresses via a loading frame (Multon and Toutlemonde 2006; Kagimoto et al. 2014; Takahashi et al. 2015; Gautam and Panesar 2016). It has been pointed out that ASR expansion is reduced as the applied compressive stress is increased. For the internal restriction by reinforcing bars, few tests have been conducted and the effects have been described qualitatively based on limited data (Jones and Clark 1996; Fan and Hanson 1998a; Mohammed et al. 2003; Haddad and Numayr 2007). Reliable expansion characteristics and relationships between the restraint degree and the rebar diameter should be investigated through a series of laboratory experiments. Morenon et al. (2017) conducted a series of experiments to investigate the impact of reinforcement restraint on ASR-expansion which could induce anisotropic cracking. Their test results show that the restraint effect of the bar will cause chemical prestress in concrete, which can reach about 1.8 MPa to 3.3 MPa depending on stirrups distribution. The results are relatively meaningful to evaluate the restraint effect of reinforcing bar.

Many researchers have reported their study on the mechanical behavior of RC structures with ASR damage experimentally and analytically (Fan and Hanson 1998b; Multon et al. 2005). Monette et al. (2002) experimented to investigate the residual strength of reinforced concrete beams damaged by ASR. RC beams were loaded to failure under sustained and cyclic loads after an accelerated ASR test. Flexural tests showed that neither ASR expansions nor load conditioning significantly affected the load-carrying capacities and stiffnesses of RC beams.

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Maeshima et al. (2016) conducted experimental studies on the fatigue life of RC slabs. Full-sized RC deck specimens with different volumetric expansions were subjected to moving load. Test results show that ASR expansion can have some beneficial impact on the fatigue life of RC slabs. Based on the present results, it can be seen that evaluating the ASR effect on the mechanical behavior of RC structures is a challenge, as the relatively slow rate of ASR. The beneficial effect of ASR may due to a relatively small expansion. Since the bond behavior between concrete and reinforcing bar is an important indicator of the mechanical properties of RC structures, Haddad and Numayr (2007) conducted an experimental program to investigate the effect of ASR on the bond behavior and concluded that ASR can significantly reduce the ultimate bond strength as high as 24%. However, reliable relationships between the bond strength and the ASR expansion have not been obtained due to limited test data. It is important to clarify this relationship through a series of accelerated ASR tests, which has benefits for understanding the deterioration characteristic of RC structures damaged by ASR.

To predict the process of ASR and its effect on mechanical behavior, numerous models were developed at both the microscopic scale (Dunant and Scrivener 2010; Saouma et al. 2015; Iskhakov et al. 2019) and the macroscopic scale (Ulm et al. 2000). Several macroscopic models have been developed to analyze the structural behavior of RC structures with ASR damage. The macroscopic models mainly focus on the field of deformation, strain, and stress at the structural scale. The chemical ASR kinetics was coupled with the constitutive laws of concrete in the model. Based on the framework, numerous parametric models (Winnicki and Pietruszczak 2008; Herrador et al. 2009) and chemo-mechanical coupling models (Multon and Toutlemonde 2006; Saouma and Perotti 2006; Grimel et al. 2010) were developed. Morenon et al. (2019) developed a poro-mechanical model to analyze the flexural performance of reactive RC beam and non-reactive RC beam. According to the model results, the first flexural crack of ASR damaged RC beam appeared at a higher load and the cracking delay phenomenon was due to the chemical prestress in the concrete induced by the restraint ASR swelling in the direction of reinforcing bar. Therefore, to reproduce the stress field of the RC structure affected by ASR, models should quantify the restraint effect of reinforcing bar.

Maekawa et al. (2008) developed a multi-scale chemo-hygral computation system (DuCOM-COM3) to cover a wider range from the behavior of CSH microstructures to the mechanical behavior of reinforced and pre-stressed concrete structures. Takahashi et al. (2014, 2015, 2016) developed a multi-scale model of ASR based on this computation system and integrated it with the poro-mechanical model (Maekawa and Fujiyama 2013). The silica gel generation, migration and the scale-dependent expansion could be simulated by the ASR model. The model has been verified by experiments and used to predict the fatigue life of ASR damaged RC decks (Takahashi et al. 2018).

This paper aims to quantify the restraint effect of reinforcing bar on ASR expansion and obtain the relationship between ASR expansion and the deterioration of the bond strength. Firstly, accelerated ASR tests for pullout specimens with different rebar diameters were conducted to measure restraint expansion. Then, pullout tests of specimens with different immersion ages were conducted to investigate the bond behavior. A simply ASR expansion model integrated with the poro-mechanical model was developed and used to simulate the experiments. The method aims to help for the assessment of the mechanical behavior of RC structures damaged by ASR in the future.

### 2. Experimental program

#### 2.1 Material and mix proportions

Ordinary concrete of C40 strength grade was adopted in this research, and ordinary Portland cement (PO 42.5) was used. Gravels with a maximum size of 20 mm and river sand with a fineness modulus of 2.4 were employed as coarse and fine aggregates, respectively. Polyethylene-based superplasticizer and ordinary tap water were used to mix them. The concrete mixture is shown in Table 1. The average cubic compressive strength was 40.54 MPa (specimens were tested at the curing age of 28 days).

Three types of deformed reinforcing bars with diameters of 12 mm, 16 mm, and 20 mm were used in this research. The yield strength and the ultimate strength were 476 MPa and 576 MPa, respectively, as summarized in Table 2.

An accelerated mortar bar test was conducted to

| Table 1 Mix proportions of concrete. |
|-------------------------------------|
| Water/Cement | Cement (kg/m³) | Water (kg/m³) | Gravels (kg/m³) | Sand (kg/m³) | Superplasticizer (kg/m³) |
|-------------|----------------|---------------|-----------------|-------------|------------------------|
| 0.49        | 398            | 195           | 1218            | 578         | 2.1                    |

| Table 2 Diameters and mechanical properties of reinforcing bars. |
|-------------------------------------|
| No. | Diameter (mm) | Yield strength (MPa) | Ultimate strength (MPa) |
|-----|---------------|----------------------|------------------------|
| 1   | 12            | 476                  | 576                    |
| 2   | 16            | 476                  | 576                    |
| 3   | 20            | 476                  | 576                    |
evaluate the reactivity of both fine aggregates and coarse aggregates, according to the recommendation of the Chinese test code for hydraulic concrete. Mortar prisms with dimensions of $25.4 \times 25.4 \times 285$ mm were cast and stored at $80^\circ$C in 1 mol/L NaOH solution to accelerate the rate of ASR. To meet the requirements of the test method, coarse aggregates should be crushed to a nominal size of 3 to 5 mm. The aggregates would be classified as non-reactive if their expansion is less than 0.10% after 14 days of immersion. As shown in Fig. 1, both the fine aggregate and coarse aggregate were reactive.

2.2 Test specimens

Figure 2 shows the details of the pullout specimens. All the specimens were $150 \times 150 \times 150$ mm, with a reinforcing bar of different diameters (12 mm, 16 mm, and 20 mm). The embedded zone of the reinforcing bar was located at the center of the concrete cube. The embedment length $l_e$ was set as $5 \ d_s$ to avoid the underestimation and dispersion of the bond strength (Okelo and Yuan 2005; Liu et al. 2017). The precise embedded lengths were applied by covering the unbound zone of the reinforcing bar with two plastic tubes on both surfaces of the specimen before concrete casting.

As shown in Table 3, 48 pullout specimens and 3 plain
prisms with no reinforcing bar for compare were cast. All the specimens were demolded after 24 h and cured under the standard environmental condition at 20±2°C and relative humidity of 90±5%.

2.3 ASR program

After 28 days of curing, all the specimens were immersed in an ASR test chamber with a water bath of 1 mol/L NaOH solution. The temperature was set maintained at 80°C to accelerate ASR (Johnson and Shehata 2016; Gautam and Panesar 2017). It should be noted that the temperature and the alkali concentration used in this experiment were relatively high to accelerate the ASR expansion. As a matter of fact, the ASR gels in such conditions will be very different from gels obtained in real structures as the viscosity of ASR gels may highly affected by the temperature and the alkali concentration. In this research, the authors mainly tried to quantify establish the relationship between bond strength and ASR expansion. The generation and the migration of ASR gel in a realistic structure will be investigated in the future. For each diameter of the reinforcing bar, two specimens were chosen to monitor the expansion of concrete over the immersion time. These specimens were taken out of the test chamber to measure the expansion every 7 days until the age of 170 days. As shown in Fig. 3, a manual length comparator with an accuracy of 1 μm was used to measure the expansion of concrete. 4 groups of measurement points were set with a distance of 4 cm away from the surface to measure the length $l_i$ of the concrete cube at $i$ days. The expansion (%) of each specimen at $i$ days can be calculated by Eq. (1):

$$\gamma_i = \frac{l_i - l_0}{l_0} \times 100$$

where $l_0$ is the initial length of the specimen and $\gamma_i$ is the ASR expansion with the immersion period of $i$ days.

As summarized in Fig. 3, to avoid the effect of temperature on the measured initial length $l_0$, the specimen was immersed in water at 80°C for 1 day before the first measurement takes place. For the measurement of the length $l_i$ of the concrete cube at $i$ days, specimens were not allowed to cool down. They were immersed in the chamber as soon as the measurement was taken.

2.4 Pullout test

The pullout tests were carried out using a universal test machine with a stiff test frame, as shown in Fig. 4. The test machine has a maximum pullout capacity of 200 kN.
The cubic specimens were installed on a steel platen and a specially fabricated spherical seat was used to prevent the eccentricity of the load. An increasing monotonically pullout load was applied to the reinforcing bar and measured by the test machine. The test was under a displacement-control mode at a constant displacement rate of 1 mm/min. All the pullout specimens were loaded up to failure (the pullout load dropped to 20% of the ultimate load or the slip reached 30 mm). Two linear variable differential transducers (LVDTs) with a measurement range of 0 to 25 mm were used to measure the average load-end displacement, and one LVDT was attached at the unload end to measure the free-end slip. The bond stress between the reinforcing bar and concrete can
be calculated by Eq. (2):

$$\tau = \frac{P}{\pi d_s l_e}$$

where $\tau$ is the bond stress, $P$ is the ultimate pullout load, $d_s$ is the diameter of reinforcing bar and $l_e$ is the embedded length.

3. Tests results and discussion

3.1. Expansion measured on pullout specimens

The mean expansion curves for the pullout specimens with a bar diameter of 12 mm (D12), 16 mm (D16) and 20 mm (D20) compared with the plain prisms (with no reinforcing bar) are shown in Fig. 5. In general, the expansion of plain prism was much higher than all the pullout specimens (D12, D16, and D20), and reached 0.448% at the immersion age of 170 days. The ultimate expansion of specimens D12, D16 and D20 at the immersion age of 170 days reached 0.344%, 0.324% and 0.277%, respectively, as summarized in Table 4.

The expansions of all pullout specimens were relatively small and no obvious difference between these specimens could be found until the age of 90 days. These similar expansions may be caused either by the relatively small swelling stress induced by ASR gels or the accuracy of the measuring instrument. After that, the difference between specimens D12, D16 and D20 became apparent. The ultimate expansion of the specimen D12 was the largest, while that of the specimens D16 was the second largest. The expansion of the specimens D20 was obviously smaller than the others. It should be mentioned that the measured ASR expansion contains both the expansion of the bonded region and the unbonded region. As a matter of fact, the unbonded length decreased as the increase of the diameter of the reinforcing bar, the measured expansion rate of the specimen may be derived from the length change including large free expansion, assuming that the expansion of the unbonded region is free. The free expansion increased with the decrease of the bar diameter and had an impact on the ASR expansion rate. Therefore the restraint effect of the diameter of reinforcing bar (shown in Fig. 5) was on the premise of a constant $l_e/d_s$. All these expansion curves reached a plateau at the age of about 90 days, the expansion seems to slow down and level off. Similar to the results of the ultimate expansions, the rate of expansion was also influenced by rebar diameters. The D20 specimens had the lowest expansion rate, and the rate decreased as the increase of rebar diameter.

It should be noted that the restraint effect of reinforcing bar (reinforcement ratio, diameter) on ASR expansion was relatively small compared with the previous study (Jones and Clark 1996). The discreteness of the experiment results may be caused by the different embedment lengths of reinforcement. In this research, the embedment length $l_e$ was set as 5 $d_s$, which may be small to obtain a large restraint effect.

The experimental results could be explained by the restraint effect of the reinforcing bar. As shown in Fig. 6, ASR is caused by a chemical process depending on the chemical composition of aggregates and the pore solution. Once the ASR gel is generated, the gel pressure may develop in concrete and cause the expansion (Swamy 2002). For the pullout specimens with reinforcing bar, the gel pressure was offset by the bond stress between the reinforcing bar and the concrete. The expansion of concrete was confined and the restraint effect increased with the increase of the rebar diameter. It was also reported the ASR gels produced may possibly have migrated and away from the original position where they had been created. The gel pressure may then be reduced with a small amount of ASR gels (Takahashi et al. 2016).

3.2. Pullout test results

3.2.1 Failure modes

The pullout test results of all the specimens are summarized in Table 5 and the failure mode of specimens with different rebar diameters and immersion time are shown in Fig. 7. It should be noted that when the specimens failed by the splitting of the concrete cover, the bond strength can not be calculated through Eq. (2). The failure is due to the mechanical property of concrete and the boundary condition of the specimen. It can be concluded
that the actual bond strength is larger than the calculated result. Therefore, nominal bond strength $\tau_{\text{nominal}}$ is defined in this paper to represent the maximum load-carrying capacity of the specimen, and it can be calculated through Eq. (2). Specimens with a rebar diameter of 16 mm (D16) and 20 mm (D20) failed by the splitting of the concrete cover along the reinforcing bar in the bond zone. The D12 specimens exhibited pull out failure without splitting or yielding. It should be noted that the failure mode was not noticeably influenced by the expansion caused by ASR, no transition of failure mode was found with the increase of the immersion time. The failure mode of pullout tests may be influenced by the concrete strength, the embedded length ($l_e$), the ratio of the concrete cover to the rebar diameter ($c/d_s$), and load conditions (Maekawa et al. 2003). In this research, $c/d_s$ seems to be the dominant factor to control the failure.

Figure 8 shows the surface cracking pattern of speci-

| No. | Specimens     | Immersion time (days) | Expansion (%) | Compressive strength after immersion (MPa) | Ultimate pullout load (kN) | Nominal bond strength (MPa) |
|-----|---------------|----------------------|--------------|------------------------------------------|---------------------------|---------------------------|
| 1   | D12-ASR-00    | 0                    | 0            | 40.54                                    | 27.33                     | 12.08                     |
| 2   | D12-ASR-07    | 7                    | 0.025        | 40.9                                     | 30.93                     | 13.67                     |
| 3   | D12-ASR-14    | 14                   | 0.038        | 43.58                                    | 36.00                     | 15.92                     |
| 4   | D12-ASR-28    | 28                   | 0.118        | 44.54                                    | 32.33                     | 14.29                     |
| 5   | D12-ASR-45    | 45                   | 0.159        | 41.33                                    | 33.27                     | 14.71                     |
| 6   | D12-ASR-60    | 60                   | 0.195        | 40.21                                    | 32.00                     | 14.15                     |
| 7   | D12-ASR-90    | 90                   | 0.282        | 34.02                                    | 29.00                     | 12.82                     |
| 8   | D12-ASR-170   | 170                  | 0.344        | 28.98                                    | 22.50                     | 9.95                      |
| 9   | D16-ASR-00    | 0                    | 0            | 40.54                                    | 58.64                     | 14.58                     |
| 10  | D16-ASR-07    | 7                    | 0.02         | 40.9                                     | 63.54                     | 15.80                     |
| 11  | D16-ASR-14    | 14                   | 0.035        | 43.58                                    | 67.65                     | 16.82                     |
| 12  | D16-ASR-28    | 28                   | 0.113        | 44.54                                    | 57.63                     | 14.33                     |
| 13  | D16-ASR-45    | 45                   | 0.145        | 41.33                                    | 55.49                     | 13.80                     |
| 14  | D16-ASR-60    | 60                   | 0.187        | 40.21                                    | 44.73                     | 11.12                     |
| 15  | D16-ASR-90    | 90                   | 0.264        | 34.02                                    | 40.84                     | 10.16                     |
| 16  | D16-ASR-170   | 170                  | 0.324        | 28.98                                    | 38.42                     | 9.55                      |
| 17  | D20-ASR-00    | 0                    | 0            | 40.54                                    | 68.93                     | 10.97                     |
| 18  | D20-ASR-07    | 7                    | 0.018        | 40.9                                     | 85.00                     | 13.53                     |
| 19  | D20-ASR-14    | 14                   | 0.034        | 43.58                                    | 88.54                     | 14.09                     |
| 20  | D20-ASR-28    | 28                   | 0.092        | 44.54                                    | 76.24                     | 12.13                     |
| 21  | D20-ASR-45    | 45                   | 0.131        | 41.33                                    | 76.16                     | 12.12                     |
| 22  | D20-ASR-60    | 60                   | 0.177        | 40.21                                    | 65.97                     | 10.50                     |
| 23  | D20-ASR-90    | 90                   | 0.237        | 34.02                                    | 59.18                     | 9.42                      |
| 24  | D20-ASR-170   | 170                  | 0.277        | 28.98                                    | 48.00                     | 7.64                      |

Fig. 6 The restraint effect of reinforcing bar on ASR expansion.
mens with an immersion age of 140 days. It can be seen that there are many ASR diffuse cracks on the surface of the specimens, some diffuse cracks propagated and become connected to each other, formed long cracks. Some of the aggregates expanded significantly and were broken. The effect of damages and cracks caused by ASR expansion on the pullout failure modes will be investigated in the future.

3.2.2 Ultimate pullout load and nominal bond strength
The ultimate pullout load and the nominal bond strength of specimens D12, D16 and D20 at different immersion ages are shown in Fig. 9. Each data point was an average for two specimens. An obvious plateau could be found for all these specimens with different rebar diameter. The ultimate pullout load and the nominal bond strength increased initially to attain their peak at 14 days, ap-

![Specimens D20: splitting of the concrete cover](image)

![Specimens D16: splitting of the concrete cover](image)

![Specimens D12: pullout of the reinforcing bar](image)

Fig. 7 The failure mode of specimens.

![D12-140](image)  ![D16-140](image)  ![D20-140](image)  ![D20-140](image)

Dx-y: x is diameter, y is immersion time

Fig. 8 Surface cracking pattern of specimens.
approximately with the expansion of 0.035%. The ratio of increase for specimens D12, D16 and D20 were 31.7%, 15.3%, and 28.4%, respectively. For specimens D16 and D20, the ultimate pullout load and the nominal bond strength decreased rapidly from 14 days until 60 days and reduced to approximately 70% of their peak values (14 days). After 60 days, the ultimate pullout load and the nominal bond strength reduced at a relatively slower rate until 170 days to reach approximately 55% of their peak values. For specimens D12, the ultimate pullout load and the nominal bond strength reduced to approximately 60% of its peak values at the age of 14 days. It should be mentioned that the results of specimens D12 at the age of 28 days were smaller than the results at the age of 45 days and these eccentricities may have been caused by experimental errors.

3.2.3 Relationship between ASR expansion and the nominal bond strength
The ultimate pullout load and the nominal bond strength of the D12, D16 and D20 specimens with different ASR expansion are shown in Fig. 10. ASR expansions had a beneficial effect on the nominal bond strength when the expansion was less than 0.035%, which is consistent with previous conclusions (Maeshima et al. 2016). However, it should be noted that the immersion solution may cause positive strains during the first days of immersion, as the specimens were not saturated at the beginning of ASR expansion. Besides, the hydration of cement may be accelerated by the high immersion temperature. As shown in Table 5, the compressive strength of concrete increased initially to attain their peak at 28 days of immersion. The change of compressive strength will decrease the negative effect of ASR (Pathirage et al. 2019).

The beneficial effect may be caused by the coupled effect of pore pressure induced by ASR expansion and the mechanical properties of concrete. Experiments of non-reactive concrete should be conducted in the future to evaluate the impact of concrete hydration and water absorption. In this research, the effect of pore pressure induced by ASR expansion and the compressive strength of concrete will be quantified firstly by the numerical analysis. When the ASR expansion exceeded 0.035%,

![Fig. 9 Ultimate pull load and nominal bond strength at different immersion ages.](image1)

![Fig. 10 Ultimate pull load and the nominal bond strength with different expansions.](image2)
both the ultimate pullout load and the nominal bond strength of all specimens with different rebar diameters decreased approximately linearly with the increase of the ASR expansion.

Based on the test results, it could be speculated that the ASR expansion is the key factor leading to the deterioration of the bond behavior between rebar and concrete. For the effect of ASR expansion on bond behavior, there would be a threshold value of the expansion. When the expansion is less than the threshold value, the nominal bond strength would be increased. The mechanism of the beneficial effect is similar to the effect of corrosion on the bond strength (Gebreyouhannes and Maekawa 2016). The pore stress caused by ASR gels induced pre-tension stress of reinforcing bar and will stiffen the bond behavior. When the expansion exceeds the threshold value, the nominal bond strength will significantly decrease. The threshold value might be influenced by the compression strength of concrete and the boundary conditions. In this research, it could be defined as 0.035%. It should be noticed that for the RC structure with a large amount of reinforcement, the deterioration of the mechanical behavior may be much smaller due to the restraint effect of reinforcing bar on the ASR expansion. With the decrease in the expansion rate, the deterioration would also trend to level off.

4. Basic models and analysis methods

In this research, the multi-scale simulation platform based on the multi-scale chemo-hygral computation system (DuCOM-COM3) was used as the basic analysis scheme, as summarized in Fig. 11 (Maekawa et al. 2008). The material properties in the microscale and the mechanical behavior at the macroscale such as the local hydration process, multi-ion transport and the multi-directional crack behavior of concrete were coupled in the life-span simulation of RC structures. In recent studies, the potassium and sodium ions in pore solution were linked with the model of ASR generation. The triple coupling of ASR, steel corrosion and the frost damage were also realized by the development of a multi-chemo-physics model (Gong and Maekawa 2019).

4.1. Constitutive laws of concrete

For simulating the mechanical behavior of concrete, a 3D finite element analytical system (COM3) was adopted in this research (Maekawa et al. 2003). As summarized in Fig. 12, the orthogonal two-crack model is first defined in the system. An elasto-plastic fracture (EPF) model and a tension stiffening/softening model were adopted to calculate explicitly the stresses parallel and normal to the active crack axis. A shear transfer model considering the crack roughness and contact friction is applied to compute shear stress from the shear strain.

4.2. ASR expansion model

Takahashi et al. (2014, 2016) developed a chemical reaction model to simulate the generation and migration of ASR gel. Based on the chemical process of ASR, the rate of ASR is formulated and the alkali concentration, updated free water content, and the reactive aggregate content were considered. The effect of the relative humidity (RH), the temperature and the amount of the consumed alkali ions and water in the reaction process on the generation rate was also taken into account. Based on the calculated volume of ASR gel, the stress formation could be automatically calculated. The proposed model has been sufficiently evaluated by experiments in terms of both uniform expansion and non-uniform expansion (Takahashi et al. 2016).

In this research, a simplified process of ASR expansion was used based on the model proposed by Takahashi et al. (2014, 2016), as summarized in Fig. 13. The authors mainly focus on the restraint effect of reinforcing bar on the expansion and the nominal bond strength. The
The chemical process of ASR, the generation and the migration of ASR gel were not considered in the present method. The generation of ASR gel was formulated by a simplified linear function. The volume ratio of ASR gel per unit volume $\alpha$, the start time $t_0$ and the end time $t_n$ of ASR were the key parameters to calculate the generation process of ASR gel.

The calculation scheme for the stress formation developed by Takahashi et al. (2014, 2016) is also shown in Fig. 13. ASR gel was regarded as a semi-liquid, both the solid part and the liquefied part coexisted. The total pore pressure $p$ could be calculated by the sum of the anisotropic pressure with solid part $p_{ai}$ and the isotropic pressure with liquid part $p_i$:

$$
 p = \frac{1}{2} \sum_i p_{ai} + p_i
$$

\(\text{(3)}\)

### Table: Constitutive Laws of Concrete

| Tension model | Compression model | Shear model |
|---------------|-------------------|-------------|
| ![Tension model](image) | ![Compression model](image) | ![Shear model](image) |

**Fig. 12** Constitutive laws of concrete (Maekawa et al. 2003).

**Fig. 13** Calculation scheme for ASR generation and stress formation (Takahashi et al. 2016).
To indicate the ratio of the solidified phase to the total ASR gel, Takahashi et al. (2014, 2016) introduced a parameter $\beta$ to calculate the anisotropic pressure with solid part $p_{asr}$:

$$P_{asr} = E_c \cdot \beta \left( \frac{V_{asr}}{3} - V_{crack,j} \right)$$  (4)

where $V_{asr}$ is the existing ASR gel volume, $V_{crack,j}$ is the crack width in the $j$th direction, $E_c$ is the stiffness of matrix.

The isotropic pressure with liquid part $p_l$ could then be calculated as Eq. (5):

$$p_l = E_c \cdot (1 - \beta) \left( V_{asr} - \sum_{j=1}^{3} V_{crack,j} \right)$$  (5)

4.3. Poro-mechanical model

To convert the microscopic pore pressure to the macroscopic stress of concrete skeleton, the poro-mechanical model (Maekawa and Fujiyama 2013) based on Biot’s theory (Biot 1963) was adopted in this research. As shown in Fig. 14, ASR gel was regarded as the medium in the voids and the cracks of the concrete skeleton. The total stress $\sigma_{ij}$ before cracking could be calculated by a simple summation of the skeleton stress $\sigma_{ij}^*$ and the pore pressure $p$ as follows:

$$\sigma_{ij} = \sigma_{ij}^* + \delta_i p$$  (6)

After cracking, the total stress $\sigma_{ij}$ could be calculated by the assumption that the pore pressure inside crack gaps acts perpendicular to the parallel crack plane:

$$\sigma_{ij} = \sigma_{ij}^* + \delta_i l \cdot p$$  (7)

where $l$ is the unit direction vector normal to a crack plane.

4.4. Basic computational scheme

The computational procedure of the method is shown in Fig. 15. The input parameters (the volume ratio of ASR gel per unit volume $\alpha$, the start time $t_0$ and the end time $t_n$ of ASR) were determined based on the measures ASR expansion. It should be noted again that the chemical process of ASR, the generation and the migration of ASR gel were not considered in the present method. The authors mainly focus on the effect of ASR expansion on the mechanical behavior of concrete. The measured ASR expansion could be directly used to predict the bond behavior and the failure mode of these specimens in this method.

5. Verification of the model

The expansion and the bond behavior of experiment specimens were simulated by the basic models and analysis methods. Meanwhile, the computational results were verified by comparing it with experimental results. Take advantage of symmetry, a one-fourth three-dimensional finite element discretization was modeled with the same dimension of test specimens, as shown in Fig. 16. The ribs of the reinforcing bar were also modeled by solid elements with real size to simulate the interaction between rebar and concrete. The modeling method was verified by the simulation of the specimens without ASR expansion. The analytical curve of the pullout load versus the free-end slip compared with the test results are shown in Fig. 17(a). The analytical principle strain distribution of specimens is shown in Fig. 17(b).

The key factor of the simulation is to reproduce the damage and the stress field of the specimens after ASR expansion. Different boundary conditions were used for the analysis of the expansion process and the bond behavior. As shown in Fig. 16, only the nodes of the reinforcing bar elements at the load-end were restricted to simulate the anisotropic expansion of concrete. Then, the nodes of the elastic elements at the upper layer were restricted to conduct the simulation of the mechanical behavior.

For the analysis of the expansion process, the volume ratio of ASR gel per unit volume $\alpha$ was used as the input...
parameter, as shown in Table 6. Based on the input parameter, the calculated ASR expansion compared with the measured expansion are summarized in Table 6. The damage and the stress field of the specimens after ASR expansion were reproduced through the ASR expansion model and it could be used as the initial states for the simulation of the pullout behavior.

Figure 18 shows the distribution of strain in the longitudinal direction of the specimens with different rebar diameters and different expansion. The expansion strain was quite non-uniform and the average strain in the bonded region was relatively small than that in the unbonded zone. An obvious restraint zone could be found near the reinforcing bar in the anchorage zone after 28 days of ASR immersion. As the increase of the rebar diameter, the embedment length of the corresponding reinforcing bar increases, which subsequently leads to an increase of the restraint zone. The restraint zone trend to decrease with the immersion ages. The average strain in the restrict zone came up to 1500 με, while some localized strain without the restrict zone (due to the free expansion of the unbonded region) could reach approximately 4000 με.

**The procedure of the analysis method**

From the measured expansion rate:

- Obtain: \( V_{\text{asr}} \)

**Input:** \( t_0, t_n \)

**calculate Eq. (3), (4), (5):**

\[
\begin{align*}
p & = \frac{1}{3} \sum \rho_n + \rho_l \\
p_{\text{asr}} & = E_{\text{asr}} \frac{V_{\text{asr}}}{V_{\text{total}}} \\
p & = \rho_0 (1 - \beta) \left( V_{\text{asr}} - \sum V_{\text{total}} \right)
\end{align*}
\]

**calculate Eq. (6), (7):**

\[
\begin{align*}
\delta_{ij} & = \sigma_{ij} + \delta_{ij} \rho \\
\sigma_{ij} & = \sigma_{ij} + \frac{\delta_{ij} \rho}{\rho}
\end{align*}
\]

**obtain: Stress-strain distribution and failure mode**

**ASR expansion model**

**poro-mechanical model**

**Fig. 15 Computational procedure of the analysis method.**

1/4 three dimensional finite element discretization

**Fig. 16 One-fourth, three dimensional finite element discretization and boundary conditions.**
μ. It can be speculated that the nonuniform strain distribution will induce the chemical prestress in concrete, and the chemical prestress will be influenced by the boundary condition of the concrete (Morenon et al. 2017).

Table 6 Calculated expansion compared with the measured expansion.

| No. | Specimens    | α       | Calculated expansion (%) | Measured expansion (%) |
|-----|--------------|---------|--------------------------|------------------------|
| 1   | D12-ASR-00   | 0.0014  | 0.025                    | 0.025                  |
| 2   | D12-ASR-07   | 0.0019  | 0.036                    | 0.038                  |
| 3   | D12-ASR-14   | 0.00495 | 0.114                    | 0.118                  |
| 4   | D12-ASR-28   | 0.0073  | 0.164                    | 0.159                  |
| 5   | D12-ASR-45   | 0.009   | 0.192                    | 0.195                  |
| 6   | D12-ASR-60   | 0.0125  | 0.287                    | 0.282                  |
| 7   | D12-ASR-90   | 0.0148  | 0.347                    | 0.344                  |
| 8   | D12-ASR-170  | 0.0013  | 0.021                    | 0.021                  |
| 9   | D16-ASR-00   | 0.0018  | 0.031                    | 0.030                  |
| 10  | D16-ASR-07   | 0.00495 | 0.113                    | 0.113                  |
| 11  | D16-ASR-14   | 0.068   | 0.149                    | 0.145                  |
| 12  | D16-ASR-28   | 0.00875 | 0.189                    | 0.187                  |
| 13  | D16-ASR-45   | 0.0115  | 0.268                    | 0.264                  |
| 14  | D16-ASR-60   | 0.0148  | 0.331                    | 0.324                  |
| 15  | D16-ASR-90   | 0.001   | 0.015                    | 0.018                  |
| 16  | D16-ASR-170  | 0.002   | 0.036                    | 0.034                  |
| 17  | D20-ASR-00   | 0.045   | 0.091                    | 0.094                  |
| 18  | D20-ASR-07   | 0.063   | 0.129                    | 0.131                  |
| 19  | D20-ASR-14   | 0.085   | 0.180                    | 0.177                  |
| 20  | D20-ASR-28   | 0.0115  | 0.235                    | 0.237                  |
| 21  | D20-ASR-45   | 0.0135  | 0.285                    | 0.277                  |

(a) Analytically calculated nominal bond behavior compared with test results.

(b) Analytically calculated principle strain distribution of specimens.

Fig. 17 Analytical results of pullout specimens with no ASR damage.
Fig. 18 Distribution of strain in the longitudinal direction (continued on page 207).
The analyzed nominal bond strengths of specimens D12, D16 and D20 with different expansion compared with the test data are shown in Fig. 19. A good agreement between the analytical and experimental results was confirmed. The bilinear relationship between ASR expansion and nominal bond strength could be simulated. The nominal bond strength increased linearly until the ASR expansion reaches approximately 0.035%. After that, the nominal bond strength decreased as the ASR expansion is increased. It could be concluded that both the ASR expansion with the restriction effect and the nominal bond strength of specimens with deferent ASR expansions could be reasonably simulated by the methods adopted in this research.

As mentioned, the compressive strength of concrete may have a significant impact on the nominal bond strength. When the ASR expansion less than 0.035%, the beneficial effect may be caused by both the pore pressure and the change of the concrete strength. To quantify the coupled effect, the effect of the compressive strength of concrete on the nominal bond strength was analyzed independently, as shown in Fig. 19 (dashed line). In the analysis, the compressive strength after immersion (as shown in Table 5) was used as the input parameters of the simulation and the ASR expansion process was not considered. Therefore, it could be assumed that the solid line denotes the single effect of the concrete strength. As shown in Fig. 19, when the ASR expansion less than 0.035%, the calculated nominal bond strength considered only the concrete strength is obviously smaller than both the experiment results and the calculated results considered the coupled effect. It could be concluded that both the pore pressure and the initial increase of concrete strength will enhance the bond behavior when the ASR expansion is less than the threshold value.

6. Conclusions

In this research, a series of pullout tests with different ASR immersion ages were conducted. The ASR expansions were measured to investigate the restraint effect of the reinforcing bar. The relationship between bond strength and ASR expansion was obtained based on the pullout tests. A simplified ASR expansion model integrated with the poro-mechanical model was adopted to simulate the experiment. The following conclusions can be drawn:

(1) The reinforcing bar has a restraint effect on the ASR expansion. The expansion of pullout specimens with rebar obviously smaller than that of plain prisms.

(2) After an immersion age of 90 days, the restraint effect on ASR expansions presents out gradually. With constant $l/d_o$, both the expansion rate and the ex-
(3) The expansions of all pullout specimens had a plateau at the immersion age of 90 days, after that the expansion trends to slow down and level off.

(4) To accelerate the ASR expansion, high storage temperature and alkali concentration were used in this research. The generation and the migration of ASR gel may be different from that of the realistic structure.

(5) A threshold value of the expansion could be defined as 0.035%. ASR expansion has some benefit to the bond strength between concrete and rebar when the expansion is less than the threshold value. The beneficial effect is caused by both the pore pressure induced by ASR expansion and the initial increase of concrete strength.

(6) When the expansion exceeds the threshold value, the bond strength of specimens decreased approximately linearly with the increase of the expansion. Based on the relationship, it could be concluded that for the RC structure with a large amount of reinforcement, the deterioration of the mechanical behavior may be much smaller due to the restraint effect of reinforcing bar on the expansion.

(7) The methods integrated the ASR expansion model and the poro-mechanical model could simulate both the ASR induced expansion with the restraint effect and the relationship between ASR expansion and the bond strength accurately. The analysis methods used in this research are useful for the assessment of the mechanical behavior of RC structures damaged by ASR in the future.

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