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Abstract

The evolution of steel bar and corrosive-crack propagation of reinforced concrete in three different solutions including MgSO4, Mg2+-SO42−-Cl−, and seawater were examined using electrochemical impedance spectroscopy. Results showed that seawater had the most serious corrosion effect on steel bar in concrete. MgSO4 combined with chloride ions could accelerate the damage process of passive film, whereas Mg(OH)2 and gypsum particles could be produced and deposited on the steel-bar surface to block the diffusion of sulfate and chloride ions into the passive film. The crack propagation of concrete in single chloride environment increased with time linearly, but the existence of MgSO4 in chloride solution could change the crack-propagation behavior of reinforced concrete from linear to nonlinear. The existence of Ca(OH)2 in MgSO4 and MgSO4-NaCl solutions could not delay the initial corrosion time but reduce the corrosion rate of steel bar by 60%–85%.

1. Introduction

The corrosion of reinforced concrete has been a research hotspot for nearly two centuries. In the USA, corrosion costs account for about 2% to 5% of the national GDP (Biezma and Cristobal 2005). Based on this calculation, the lost caused by corrosion in China is about 1500 billion RMB annually (Hou et al. 2012). Chloride-induced rebar corrosion is one of the major damage forms of reinforced concrete in marine environment, salt lake, and saline soils areas (Shi et al. 2012; Yu 2004). Under these conditions, depassivation and corrosion of steel bar can lead to localized formation of porous oxide layers at the steel/concrete interface. The transformation of metallic ions into oxides is accompanied by a volume increment up to two to six times, which is the root cause for reinforced concrete expansion and crack. Oxygen and corroded ions pass through the crevices easily to accelerate steel bar corrosion rate. Irreversible damage of reinforced concrete processes, such as concrete crack, capacity loss, and structure destruction, are created (Williamson and Clark 2000; Bilik and Holly 2013; Tapan and Aboutaha 2011). Magnesium sulfate attack is another problem for the durability of concrete structures in the above mentioned areas, where the concentration of Mg2+ and SO42− are almost 1600–83 500 and 3300–63 000 ppm, respectively (Moradillo 2012; Liu 2001; Brown and Aboutaha 2000). The transformation of the cementitious CSH gel to the non-cementitious magnesium silicate hydrate mush (MSH), which has very little strength, is the main reason for the deterioration of concrete during MgSO4 attack. Expansive corrosion productions, including CaCO3 and secondary Aft, are also formed in concrete subjected in MgSO4 attack (Beaudoin et al. 2001; Hekal et al. 2002; Skaropoulou et al. 2009).

Three different models, including adsorption leading to local passive film dissolution, penetration of anions in the passive film leading to weakening of the oxide bonds, and passive film break down at defects, such as cracks and dislocations, are frequently quoted to explain the effect of chloride ions on passive films and the influence of pitting corrosion (Li et al. 2011; Zhao et al. 2013). The formation and dissolution of passive films, pitting corrosion of iron, and corrosive cracking of reinforced concrete in Na2SO4 environment have also been reported (Giu and Devine 1994; Jin et al. 2015). When reinforced concrete is subjected to attack of MgSO4, Sol et al. (2015) found that severe surface damage and high corrosion of carbon steel in the concrete. Jarrah et al. (1995) studied the corrosion potential-time curves for steel bar in plain and blended cement concrete specimens placed in 2.1% sulfate solution composed of sodium sulfate and magnesium sulfate for about two years; the passivity phenomenon was still observed on the steel surface. Experimental results from Dehwah et al. (2002) showed that a marginal decrease in the Icorr was noted when the concentration of magnesium sulfate was increased from 2.5% to 4.0%, the opposite tendency was observed when the concentration of magnesium sulfate was increased from 0 to 2.5%. Based on these studies, it can be concluded that positive and negative effects simultaneously exist between MgSO4 and cement hydration on...
corrosion of steel bar in concrete. However, the reasons for the positive and negative effects and the quantitative influences of MgSO4 on the corrosion of steel bar and induced corrosive cracking of reinforced concrete remain unclear.

The mechanism of deterioration for reinforced concrete exposed to seawater, seashore, and salt lake environment may become even more complex because of the interaction of multiple ions and materials (Geng et al. 2015; Tumidajski and Chan 1996; Yildirim and Sumer 2013). Based on experiment results of cracked concrete in an artificially created chloride ion-induced corrosion environment, the relationship between crack widths and corrosion rate at the early age of exposure was proposed by Mohammed et al. (2012). Especially, the valuable data from investigation of 15-year-old uncracked and precracked concrete made with different kinds of cement exposed to a tidal pool, experimental results from Mohammed et al. (2002) shown that small crack (width less than 0.5mm) undergoes healing and this healing caused the corrosion rate to fall or even reach zone during 15 years exposure. And presence of visible voids at the steel-concrete interface caused the formation of corrosion pits irrespective of cement type. Mo¨lder (2007) reported that the positive influence of magnesium on the corrosion behavior of freely corroding steel in seawater is caused by calcium carbonate precipitating as aragonite. Pradhan (2014) found, aside from sulfate ion concentration, cement type, w/c ratio, and chloride ion concentration also affect the relative resistivity and corrosion current density of the composite solutions of sodium chloride and magnesium sulfate. However, the interaction influence between MgSO4, chloride ion and cement hydration on the corrosion behavior of steel bar remains unclear. The precise role of MgSO4 in chloride-induced corrosive-crack propagation of reinforced concrete has not yet been clarified.

Investigating the corrosion process of steel bar in concrete remains a challenge because the penetration of corrosion ions into concrete is a long-term process. Thus, researchers have carried out their studies on reinforced bar corrosion in simulated concrete pore solution (Abd El Aal et al. 2009; Liu et al. 2014) or with the use of accelerated corrosion technique (Kashani et al. 2013; Yuan and Ji 2009). In present work, a comprehensive experimental program that involving the electrochemical behavior and corrosion processes of steel bar in Ca(OH)2 solutions in the presence of NaCl and MgSO4 as aggressive salts for different immersion times were conducted. The corrosion monitoring of the steel bar was achieved by electrochemical impedance spectroscopy (EIS). The initial cracking time and cracking process of the reinforced concrete mixing with seawater, NaCl, and composite solution of MgSO4 + NaCl were also studied by constant potential accelerated method.

2. Experiment and materials

2.1 Materials and specimen preparation

Round carbon steel with a length of 30 mm and a diameter of 10 mm was used as steel bar. The chemical composition of the carbon–steel bar include (in wt %) 0.22% C, 0.30% Si, 0.65%Mn, 0.05% S, 0.045% P, and residual Fe. A copper wire lead was soldered to one end of the samples. The flank and the end surface with a thick copper wire were sealed with epoxy resin, leaving a free surface of about 0.785 cm2 exposed. The tested surface was polished with SiC water polishing papers with grits of 400#, 800#, and 1500#. The steel bar specimen was ultrasonically degreased in acetone, washed in distilled water, and then dried at room temperature for electrochemical test.

Chinese standard P.I.52.5 Portland cement, with a compressive strength of 59.8 MPa at an age of 28 days was used in this study. Class I fly ash (Chinese standard) and S95 GGBS were employed to replace cement. The chemical composition of cement, fly ash, and GGBS is shown in Table 1.

The coarse aggregate was crushed granite with a maximum size of 25 mm and a bulk density of 1420 kg/m3. River sand with fineness modulus of 2.6 and a bulk density of bulk density of 1480 kg/m3 was used as fine aggregate. A polycarboxylic super plasticizer was used, and its dosage was adjusted to keep the slump of fresh concrete at the range of 140 and 180 mm. The mixing water, containing tap water, chloride solution (1%NaCl), seawater, and composite solution (1% NaCl+0.5% MgSO4), was used to accelerate the corrosion of steel bar in reinforced concrete. The concrete mixtures were prepared with an effective water-to-cement ratio (w/c) of 0.33, with the total cement content of 450 kg/m3 and sand percentage was 0.4. The air content of L50 and LF50 fresh concrete was 1.5 and 1.7, respectively. Based on considerable trials and durability tests, high content mineral admixtures including GGBS and Fly ash could improve the workability of fresh concrete, chloride bound capacity and crack resistance capacity of harden concrete. Therefore, the optimized mixture proportion LF50 mixed with about 31% GGBS and 18% fly ash and with w/c=0.33 was identified and had used in lining concrete structure of Qingdao Underground. The influence of high content mineral admixture on corrosion of steel bar in concrete may be occurred, the comparative concrete L50 with the same

<table>
<thead>
<tr>
<th>Constituent</th>
<th>SiO2</th>
<th>Al2O3</th>
<th>Fe2O3</th>
<th>CaO</th>
<th>MgO</th>
<th>TiO2</th>
<th>Na2O</th>
<th>K2O</th>
<th>SO3</th>
<th>Cl-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>21.8</td>
<td>5.42</td>
<td>3.44</td>
<td>63.85</td>
<td>1.26</td>
<td>0.36</td>
<td>0.57</td>
<td>0.33</td>
<td>2.26</td>
<td>0.00</td>
</tr>
<tr>
<td>GGBS</td>
<td>32.87</td>
<td>13.40</td>
<td>1.34</td>
<td>41.06</td>
<td>5.64</td>
<td>1.59</td>
<td>0.45</td>
<td>0.54</td>
<td>2.68</td>
<td>0.01</td>
</tr>
<tr>
<td>Fly ash</td>
<td>51.28</td>
<td>32.00</td>
<td>4.23</td>
<td>3.76</td>
<td>0.75</td>
<td>1.43</td>
<td>1.02</td>
<td>0.38</td>
<td>2.50</td>
<td>0.02</td>
</tr>
</tbody>
</table>
w/c and total cement content as LF50 was prepared. The mixture proportions and the corresponding compressive strengths of the concretes are given in Table 2.

Reinforced concrete specimens were prepared as a square section (100 mm×100 mm×400 mm). The longitudinal reinforcements were made of two bars: 12 mm-diameter deformed carbon–steel bars at the top with an effective cover of 30 mm and 8 mm diameter stainless steel bar at the bottom with an effective cover of 20 mm. The carbon–steel bars were cleaned and coated with cement paste, followed by epoxy coating at the concrete-air interface. The surface of the deformed carbon–steel bar was polished with a 200# polishing paper. The steel bars were degreased by acetone before being placed in the mold. Reinforced concrete samples were cast and placed at room temperature in the mound, and then removed after 48 h. All specimens were cured at 20±3 °C and 95% relative humidity for 26 days.

2.2 Electrochemical experiments

Five sets of electrolyte solutions were selected to simulate the corroded concrete pore solutions: (1) saturated Ca(OH)2 solutions with 0.12% (wt.%) NaCl; (2) saturated Ca(OH)2 solutions with 0.25%, 0.5%, and 1.0% (wt.%) MgSO4; (3) 0.25%, 0.5%, 1.0% (wt.%) MgSO4; (4) saturated Ca(OH)2 solutions with 1.0% NaCl plus 0.5% (wt.%) MgSO4; and (5) Seawater.

Prior to the measurements, the steel bars were immersed in saturated Ca(OH)2 solution for 7 days to promote a passive film to simulate the field conditions (Poursaee and Hansson 2007). Three parallel steel bar samples were used for each solution. Electrochemical experiments were performed in a classical three-electrode cell assembly with carbon–steel bar as working electrode, a 2.0 cm×2.0 cm platinum foil as counter-electrode, and a saturated calomel electrode (SCE) provided with a Luggin capillary as reference electrode. The electrochemical measurements were performed at room temperature with Princeton VersaSTAT 3Potentiostat/Galvanostat. EIS measurement was carried out at the frequency range of 100 kHz to 10 mHz at steady open circuit potential (OCP) disturbed with an amplitude of 10 mV. The EIS data were analyzed by ZsimpWin software. The polarization resistance (R_P) and the passive film resistance (R_f) were calculated according to the equivalent-circuit simulation. The instantaneous corrosion rate (i_corr) of the steel bar could be obtained from the polarization resistance (R_P) through the Stern–Geary Equation (1):

\[ i_{corr} = \frac{B}{R_P} \]

where B is the function of Tafel slopes. For steel bar in the concrete or in the simulated concrete pore solution, B values of 26 mV for the active state and 52 mV for the passive state have been proposed (Andrade and Gonzalez 1978).

2.3 Accelerated corrosion of reinforced concretes

After concrete specimens were cured for 26 days; their reinforcements were subjected to accelerated corrosion current supplied by potentiostat through deformed carbon–steel bar (connected to the positive electrode) and stainless steel bar (connected to the negative electrode). The electric potential was kept constant as 30 V. The surface of the reinforced concrete specimens was observed daily. The crack width was determined with a crack test instrument (precision of 0.01 mm). After the completion of accelerated corrosion, the corroded reinforced bar was removed from the concrete specimens, cleaned, and weighed (Chung et al. 2008).

2.4 Surface characterization of corroded steel bar

The carbon–steel bars were immersed in different corrosion solutions, and the surface morphologies of the corroded steel bar were analyzed by scanning electron microscopy (SEM; KYKY-2800B).

3. Results and discussion

3.1 Steel bar in the MgSO4 solutions

The EIS plots of the steel bar immersed in 0.25% to 1.0% MgSO4 solution for 1 h is shown in Fig. 1. Only a single capacitive loop could be observed in the Nyquist plots for the steel bar immersed into 0.25% and 0.5% MgSO4 solutions. Meanwhile, aside from a high frequency loop, a low frequency straight segment was observed in the Nyquist plot for the 1.0% MgSO4 solutions. Models A

![Fig. 1 Nyquist plots of steel bar in MgSO4 solutions.](image-url)
Corrosion products were similar; however, several small particles were deposited on the surface of the steel bar and the corrosion products when steel bar was immersed in mixed MgSO₄-Ca(OH)₂ solution. Consequently, when the width and number of cracks were reduced and the porosity of corrosion products was decreased, the corrosion velocity of the steel bar also decreased.

### 3.2 Steel bar in magnesium-sulfate-chloride solutions

The evolution of corrosion products on the surface of steel bar immersed in seawater (Solution 1), 1.0% NaCl solution plus 0.5% MgSO₄ (Solution 2), and saturated Ca(OH)₂ solution with 1.0% NaCl plus 0.5% MgSO₄ (Solution 3) for different times was observed. Green rust and pitting were first observed on steel-bar surface, which gradually changed to orange rust. The amount of corrosion products increased with time, and mainly deposited on the edge or the central area of the steel bar. In addition, the corroded area of the steel bar in different solutions followed the order of Solution 1 > Solution 2 > Solution 3. The initial time of the corrosion products to appear on the steel-bar surface in the above three solutions was observed.

![Fig. 4 Nyquist diagrams of steel bar immersed in saturated Ca(OH)₂ solutions with different concentration of MgSO₄: (a) 0.25%, (b) 0.5%, and (c) 1.0%.

![Fig. 5 Rᵢ of the steel bar in saturated Ca(OH)₂ plus Mg(OH)₂.

![Fig. 6 Rᵢ and i_corr of the steel bar in saturated Ca(OH)₂ plus different concentrations of MgSO₄. (a) Rᵢ; (b) i_corr.](image-url)
The time for serious corrosion of steel bar in the above mentioned solutions is 26, 80, and 180 min. The EIS diagrams of the steel bar immersed in the above solutions were tested and shown in Fig. 8. The curves presented similar law in different periods when steel bar was immersed into Solutions 1 and 2; only one loop was observed in the Nyquist plots. However, when the steel bar was stored in Solution 3, the Nyquist plot presented a capacitive loop plus a low frequency short straight segment. The radius of the capacitive loop was gradually reduced with immersion time for the steel bar in the first two solutions. However, the loop radius in Solution 3 was reduced first, then remained stable, and finally decreased after 6 h of immersion.

Two equivalent circuit models were used to fit the experimental data shown in Fig. 2. The EIS diagrams of the steel bar immersed in different types of solutions at different times, as shown in Fig. 9. Given that high concentration of chloride ion in seawater, the resistance of seawater was low. The existence of Ca(OH)₂ in the MgSO₄-NaCl solutions increased the resistance of the corrosion solutions by about 10% within 8 h of immersion. This result could be attributed to the fact that Mg(OH)₂ and gypsum, formed by MgSO₄ reaction with Ca(OH)₂, dispersed in the electrolyte solution and increased the resistance.

The Rᵢ of the steel bar in all electrolyte solutions was reduced sharply in the first 2 h because of corrosion reaction. With the increase in deposition of the corrosion products on steel-bar surface, Rᵢ remained stable with immersion time. In addition, the Rᵢ of steel bar in Solution 3 was higher than that in the other two solutions. Meanwhile, the high pH induced by Ca(OH)₂ in the electrolyte solution delayed the undermining of the passive film.

At the initial 30 min, steel bar in Solution 3 was not corroded. Thus, the Rᵢ of the steel bar was the highest, while the corrosion current density was only 8 µA/cm². With the increase in immersion time, Rᵢ declined sharply because of corrosion initiation. The corrosion rate of steel bar then remained stable because of the positive protection effect of the high pH value and the deposition of Mg(OH)₂. In Solutions 1 and 2, The Rᵢ of the steel bar decreased with time because of constant corrosion reaction. Therefore, the corrosion rate of the steel bar in different solutions showed the following order: Solution 1 > Solution 2 > Solution 3. The existence of Ca(OH)₂ in the MgSO₄-NaCl solution could not delay the initial corrosion time, but could prolong the corrosion process and reduce the corrosion rate.

The microstructure of the corroded steel bar in three solutions is shown in Fig. 10. When steel bar was immersed in Solution 1, large amount of globular corrosion products were distributed all over the steel-bar surface, and the integrity of the passive film was destroyed completely. When steel bar was immersed in Solutions 2 and 3, small amount of undamaged passive film could still be observed on the surface of steel bar. The corrosion products mainly included two layers. The first layer was plate-like rusts with cracks tightly attached to the steel-bar surface. The second layer was a large amount of small and porous grainy corrosion products uniformly.
distributed on the first layer. Similarly, several connected pores in globular and grainy corrosion products were observed. However, the porosity of corrosion products on the steel bar in Solutions 2 and 3 was less than that in Solution 1. Therefore, the corrosion degree of the steel bar in Solution 1 was the most serious; the corrosion rate of the steel bar in Solution 1 was also higher than that in Solutions 2 and 3.

A close observation revealed that short column product, gypsum, was deposited on the surface of porous grainy corrosion products when the steel bar immersed in Solution 3, which would block the corrosion ions in penetrating the inner layer of steel bar. This result is one reason why the corrosion velocity of the steel bar in Solution 3 was the minimum.

### 3.3 Corrosive cracking of reinforced concrete

Reinforced concretes mixed with different solutions, such as, seawater (C1), 1% NaCl+0.5% MgSO₄ (C2), 1% NaCl (C3) and tap water (C4), were polarized by a constant voltage of 30 V. The time of crack initiation and reaching the maximum crack width of 0.2 mm for different concrete systems are shown in Fig. 11.

The results clearly showed that the cracking time of C1 was the minimum, whereas C4 was the maximum. Apparently, chloride ions could result in more steel rusts to form on the steel bar, which would accelerate cracks of the reinforced concrete. The total percentage weight loss...
of the steel bar in different concrete systems is shown in Fig. 12. The corrosion degree of the steel bar in L50 reinforced concrete had the following order: C1 > C2 > C3 > C4, in accordance with the results obtained from Fig. 11.

Regardless of the mixing solution, the time of crack initiation and reaching the maximum crack width of 0.2 mm of L50 was shorter than that of LF50. The results may be attributed to the lower of strength of L50 compared with that of LF50; thus, oxide and water could penetrate into the concrete easily.

Figure 11 shows that the time of crack initiation and crack expansion of L50 was shortened when chloride salt water was added to 0.5% MgSO4 solution as mixing water. Meanwhile, an opposite trend was observed for the LF50 concrete. The time of crack initiation and crack expansion is mainly effected by the tensile strength of concrete and the expansion press of the corrosion products on the steel-bar surface. When sulfate ions were presented in the concrete, the bound chloride ion content decreased and the amount of free chloride ion-induced corrosion products increased (Jin et al. 2009). In addition, MgSO4 would react with the cementitious compounds, promote the dissociation of calcium hydroxide and de-calcification of C-S-H, and continuing formation of brucite and secondary gypsum, and then fill the pores of the concrete (Lee et al. 2005). Large amounts of brucite and secondary gypsum lead to microcracking and decrement of concrete compactness. Therefore, the strength and dynamic elastic modulus of concrete under attack of sulfate-chloride solution increased firstly, and then decreased with corrosion time (Jin et al. 2007; Yang et al. 2012). Therefore, the time of crack initiation and crack expansion of L50 mixed with 1% NaCl+0.5% MgSO4 was less than that of 1% NaCl. When 16% fly ash and 33% GGBS were used to replace Portland cement to prepare the LF50 concrete. Since GGBS was much finer than PC, it filled the micropores in the cement paste and
improved the mechanical properties and durability of concrete by reducing permeability and porosity. The mechanical and physical properties of GGBS concrete decreased at a smaller rate than that of the PC concrete subjected to attack of sulfate salt (Tu¨rkmen 2003). So, the formation and growth of brucite and secondary gypsum was delayed; instead, small amounts of corrosion products compacted the concrete and improved the crack resistance of concrete. Consequently, the time of crack initiation and crack expansion of LF50 mixed with 1% NaCl+0.5% MgSO4 was delayed.

For different mixing solutions, the changing curves of the crack width with time are shown in Fig. 13. The results indicated that the crack propagation of concrete in single chloride environment increased with time linearly; hence, the elastic modulus of the corrosion products and the tensile strength influenced by chloride ion content and corrosion time should be neglected. Therefore, the expansion pressure of the corrosion products increased with time, and resulted in linear cracking of the reinforced concrete. In the electrochemically accelerated corrosion experiment, the high speed of steel corrosion may have resulted in insufficient time for corrosion products to fill the cracks. After the crack penetrates the concrete cover, some corrosion products dissolve in the solution and are carried away from the rebar by the solution, lining and penetrating the edges of cracks (Zhao et al. 2013). Because these corrosion products couldn’t penetrate into concrete and only accumulated in cracks, the expansion pressure induced by corrosion products would increase linearly with time. However, given that the steel bar in reinforced concrete was surrounded by MgSO4 plus chloride ions, the cracking process of the reinforced concrete was nonlinear. Although the crack width of reinforced concrete increased with time linearly in early corrosion period, the crack propagation of L50 and LF50 in later stage increased nonlinear with time at a relative high and slow rate, respectively. Fig. 10 showed that the corrosion products were compact and massive as concrete mixing with seawater, while became loose and granulate as concrete mixing with composite solution. Moreover, sulfate attack initially had a positive influence on the dynamic modulus of concrete, and the modulus would be decreased with increasing time (Yang et al. 2012). Due to concrete mixed with sulfate solution cured

![Fig. 12 Total percentage weight loss of steel bar in two types of reinforced concretes.](image)

Fig. 12 Total percentage weight loss of steel bar in two types of reinforced concretes.

![Fig. 13 Changing curves of the crack width with time for the two types of concretes in different solutions.](image)

Fig. 13 Changing curves of the crack width with time for the two types of concretes in different solutions. (a) L50; (b) LF50.
for 26 days and accelerated corroded for 5-10 days, the elastic modulus of concrete would decrease and be lower than that of concrete mixed with chloride solution. So, the decreased elastic modulus of concrete and the looseness of the corrosion products would disperse the swelling stress.

4. Conclusions

Based on experiments of steel bar in magnesium-sulfate-chloride salt solutions and corrosive crack of reinforced concrete mixed with corrosion solutions accelerated by constant potential, the following conclusions have been drawn:

1. The negative influence of magnesium sulfate on the corrosion behavior of the steel bar is the breakdown of passive film by sulfate ion. The corrosion rate of the steel bar linearly increased with the concentration of magnesium sulfate in the simulated solution. And it’s positive influence on the corrosion behavior of steel bar in concrete is attributed to the precipitation of brucite and gypsum on steel-bar surface and blocking the sulfate and chloride ions from penetrating into passive film.

2. In seawater, the time for corrosion initiation of the steel bar was the shortest, which only needed 14 min. The time of initial cracking and reaching the maximum crack width of 0.2 mm of the reinforced concrete mixed with seawater was also the minimum.

3. Low concentration of magnesium sulfate caused microstructure and mechanical properties of Ordinary cement concrete to decrease, but improved the properties of high performance concrete with high content mineral admixtures in short term exposure period. As 0.5% MgSO₄ adding to chloride solution, the time of crack initiation and crack expansion of Ordinary cement concrete was shortened, as opposite to high performance concrete.

4. The crack propagation of concrete in single chloride environment linearly increased with time. The existence of magnesium sulfate in the chloride solution changed the crack propagation of reinforced concrete from linear to nonlinear.

Acknowledgments

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