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Flexural Behaviors of Ecological High Ductility Cementitious Composites Subjected to Interaction of Freeze-Thaw Cycles and Carbonation

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Abstract
To explore flexural behaviors of ecological high ductility cementitious composites (Eco-HDCC) for bridge deck link slab under severe service conditions, interaction experimental schemes of freeze-thaw cycles and carbonation were designed. Factors such as interaction cycle and preloading stress level were considered. Carbonation front and pore structure of Eco-HDCC were analyzed. The results show that ultimate flexural strength and ultimate deflection of Eco-HDCC decrease when interaction cycle or preloading stress level increases. Besides, all flexural load-deflection curves exhibit four stages: linear elastic, non-linear, deflection hardening and deflection softening stage. In addition, carbonation front of Eco-HDCC increases when interaction cycle or preloading stress level increases. With the same depth range in Eco-HDCC, pore structure deteriorates as interaction cycle increases, and deterioration degree of pores decreases as depth increases. For general consideration, after interaction cycles of 15, flexural property of Eco-HDCC with preloading stress level of 0.5 can be adopted for bridge deck link slab design with the aim to safety.

1. Introduction
Expansion joint is installed between adjacent simple-span girders to accommodate tension-compression deformation caused by temperature variance, shrinkage and creep, etc. However, the bearing capacity of girders may be affected by water leakage and flow of deicing chemicals through joint. Thus, an approach to alleviate the problem involves the elimination of expansion joint in bridge engineering (Li et al. 2003). Bridge deck link slab is a promising choice to replace the expansion joint, and the whole bridge deck will be continuous. Notably, bridge deck link slab not only bears tension-compression deformation, but also bears negative bending moment caused by traffic loading.

High ductility cementitious composites (HDCC) is a kind of fiber-reinforced cement-based composite material, which has an average ultimate tensile strain of more than 0.5% and an average crack width of less than 200 μm (JSCE 2008). HDCC has been applied in bridge deck link slab, and the monitor results indicate that HDCC meet the design requirements (Michael and Li 2009; Guo et al. 2016).

Bridge deck link slab is exposed to natural environment, and its durability is an important concern in terms of reducing the cost of new construction and maintenance for bridge engineering. From the view point of durability for bridge deck link slab made by HDCC, freeze-thaw cycle is responsible for HDCC deterioration in cold climates. In addition, carbonation can be identified as the most common deterioration cause affecting the durability of steel rebar reinforced HDCC structures (He et al. 2016). Moreover, bridge deck link slab is subjected to complex environment according to seasonal changes per year. For example, in northern China, bridge structure is usually subjected to freeze-thaw cycles from December to February and exposed to carbonation environment from March to November. Thus, interactive deterioration of freeze-thaw and carbonation should be considered for HDCC.

So far, most literatures related to HDCC durability focus on a single factor. The mechanical property of HDCC exposed to freeze-thaw environment was more excellent than that of normal concrete, and this can be attributed to crack resistance of fibers (Sahmaran et al. 2012; Nam et al. 2016). After freeze-thaw cycles of 0 ~ 300, the ultimate flexural strength for HDCC specimen with thickness of 15mm showed decrease trend, and ultimate deflection increased after 0 ~ 150 cycles while decreased after 200 ~ 300 cycles (Chai and Fei 2018). In addition, the ultimate flexural deflection of HDCC sub-
Studies also concluded that crack self-healing was obvious with a crack width of less than 43 μm. Calcium carbonate (CaCO₃) and calcium hydroxide (Ca(OH)₂) proved the self-healing performance of HDCC were also effective. Notably, the productions that interact with CO₂, carbonation for Eco-HDCC, and the cost of Eco-HDCC was only one third of that of traditional HDCC (Zhang et al. 2014). The interactive effects of freeze-thaw cycles and carbonation on flexural property of Eco-HDCC were investigated. Pre-crack was also made in order to evaluate the crack width effect on flexural performance. In addition, DSC-TG and XRD methods were used to calculate the content of Ca(OH)₂ and CaCO₃. Carbonation front with different preloading level was determined by the transition point of content for Ca(OH)₂ and CaCO₃. Moreover, pore structure of Eco-HDCC was also analyzed by mercury intrusion porosimetry (MIP) device.

### 2. Experimental program

#### 2.1 Materials

Materials used in the study were all provided by Nanjing local manufacturers. P·II 42.5R Portland cement (C) and Class F fly ash (FA) were used as the binding materials. River sand (S) was selected as the aggregate. Its density, fineness modulus and maximum diameter were 1570 kg/m³, 1.68 and 1.18 mm, respectively. The normal PVA fiber (PVAF) produced in China with characteristics of high tensile strength and high elastic modulus was selected. The main properties are presented in Table 1. Polycarboxylate Superplasticizer (PS) was used to adjust the workability of the fresh Eco-HDCC paste. These materials were mixed by the tap water (W). The mixture proportion of Eco-HDCC with compressive strength of 43.4 MPa is shown in Table 2.

#### 2.2 Specimen preparation

Concrete mixer was used to prepare Eco-HDCC specimens. The procedures were as follows: all solid ingredients, including cement, fly ash, river sand and polycarboxylate superplasticizer powder were mixed for 120 s. Then water was added and mixed for 240 s. Stay for 30 s to eliminate bubbles. Finally, fibers were added slowly to the mixture and mixed for another 3 min.
and mixed for 120 s.

Three 100 mm cubic specimens were prepared for compressive strength test. Prism specimens with dimensions of 100 mm × 100 mm × 400 mm were used for flexural property test.

All fresh Eco-HDCC specimens were placed in laboratory with the temperature of (21 ± 5)°C, and demolded at age of 24 h. Then specimens were cured in normal curing condition with the temperature of (23 ± 2)°C and relative humidity of (95 ± 2)% for 28 days.

2.3 Test procedures

(1) Interaction test of freeze-thaw cycles and carbonation

In northern China, Eco-HDCC bridge deck link slab is subjected to interactive effects of freeze-thaw cycles and carbonation. The order of interaction has a significant impact on the experimental results. Mechanical property for concrete with interaction test sequence of freeze-thaw and carbonation decreased more severely than that for concrete with reverse interaction test sequence (He et al. 2016). In order to make the test results more close to the actual situation of the project, interaction test was designed according to the climates characteristics in northern China. Freeze-thaw occurs from December to February and cycles can be 118 per year (Li 2015). Carbonation phenomenon may occur from March to November and last about 9 months. With reference to the relationship between test in field and accelerated test in laboratory, freeze-thaw cycles of 118 in field can be equivalent to 10 cycles in laboratory and nine months carbonation in field can be equivalent to 9.7 h in laboratory (Li 2015; Zeng 2013). Thus, freeze-thaw cycles of 10 and carbonation of 9.7 h for accelerated test in laboratory can be equivalent to conditions in field per year in northwest region.

Traditional expansion joint is designed at least 15 years according to bridge engineering code (ISPRC 2015), and bridge deck link slab should be designed at least 15 years. Interaction cycles of Eco-HDCC in laboratory can be set as 0, 1, 3, 5, 10 and 15.

The detailed interaction test of Eco-HDCC for per cycle was presented as follows: water immersion (4 days) + 10 freeze-thaw cycles + 60°C oven dry (2 days) + 9.7 h carbonation. In addition, freeze-thaw cycle and carbonation tests were all according to concrete durability code (NSPRC 2009). Rapid freeze-thaw testing machine was used for freeze-thaw cycle, and the test liquid was water. Moreover, the rapid freeze-thaw cycle consisted of alternatively lowering the temperature of specimens from 4°C to -18°C and raising it from -18°C to 4°C over 4 h. The accelerated carbonation test was carried out by a sealed chamber with 20°C in temperature, 70% in relative humidity and 20% in CO2 concentration (NSPRC 2009; Chai and Xu 2018).

(2) Flexural property

Flexural property test of Eco-HDCC was conducted according to fiber reinforced concrete standard (CECS 13 2009), and four-point bending type was adopted. The loading rate was 0.2 mm/min. In addition, two linear variable differential transformers were used to measure the mid-span deflection.

In addition, preloading stress level was considered in order to induce crack for Eco-HDCC specimen before interaction test. Three preloading stress levels of 0.3, 0.5, and 0.7 were determined. Preloading stress level of 0.3 was the elastic limit point, and stress level of 0.5 was the first cracking point according to the flexural stress-deflection curve of Eco-HDCC. Stress level of 0.7 was located at the multiple cracking stage of flexural stress-deflection curve for Eco-HDCC. Interaction test of Eco-HDCC specimen was performed after preloaded.

(3) Carbonation front

Five surfaces of Eco-HDCC specimens were sealed by paraffin, and surface with pure moment zone was subjected to freeze-thaw cycle and carbonation. The exposure surf ace had a dimension of 100 mm × 400 mm. Powders were drilled from pure moment zone after predetermined interaction cycles. The drilled interval was 1 mm along exposure direction, and powders were screened by 0.075 mm sieve. Intensity of Ca(OH)2 and CaCO3 was examined by XRD analysis. Based on the depth range with CaCO3 existing, DSC-TG test was conducted to calculate the contents of Ca(OH)2 and CaCO3.

(4) Pore structure

Mercury intrusion porosimetry (MIP) analysis was used to characterize the pore size distribution of Eco-HDCC subjected to interaction cycles. Pore structure of Eco-HDCC varied with the specimen thickness. To ensure the MIP results were representative, stratified sampling was used in the study. Sample slice for MIP test in Eco-HDCC specimen was taken every 10 mm along cut direction, as shown in Fig. 1. Eco-HDCC specimen with preloading generates crack exposed to interaction cycles, and the MIP curve was not accurate due to the existing crack. Thus, sample for MIP test was cut from Eco-HDCC specimen with un-preloading. Samples for MIP test were listed in Table 3. Besides, sample slice was cut into small particles with dimension of 5 mm × 5...
mm × 5 mm and particles were dried to constant weight at 50°C prior to MIP test.

3. Results and discussions

3.1 Crack trend
Although three preloading stress levels were considered in the Eco-HDCC test program, only preloading stress level of 0.7 can induce crack. Notably, Eco-HDCC specimen with preloading stress level of 0.5 generates crack after 5 interaction cycles. The observations for cracks in Eco-HDCC specimen are shown in Fig. 2. Crack width is about 28 μm for preloaded Eco-HDCC specimen with preloading stress level of 0.7, and crack width becomes about 30 μm for specimen after 15 interaction cycles. Eco-HDCC specimen with preloading stress level of 0.5 cracks with 5 interaction cycles and the crack width is 20 μm, while the crack width is 28 μm with 15 interaction cycles. It can be seen that once crack generates, the crack will worsen when Eco-HDCC are exposed to interaction cycle. There is no crack in Eco-HDCC specimen with preloading stress level of 0 and 0.3 subjected to interaction cycles.

Although some researchers have already concluded that crack will be self-healed with the width less than 50 μm (Yıldırım et al. 2018; Zhu et al. 2012, 2016), the crack will worsen with interaction of freeze-thaw cycle and carbonation in the study. Hydration reaction for un-hydrated cement particle, carbonation effect for carbon dioxide and pozzolanic reaction for fly ash exist during the interaction process of Eco-HDCC. However, surface of Eco-HDCC specimen peels off and cracks after subjected to freeze-thaw cycle. Thus, the crack width measured on the specimen surface is larger with 15 interaction cycles. Besides, as the preloading stress level of 0.5 is first cracking point, Eco-HDCC specimen subjected to 5 interaction cycles cracks. Once Eco-HDCC specimen cracks, the width of existing crack will increase.

3.2 Carbonation front
Carbonation front is a significant index to reflect the deterioration degree of Eco-HDCC specimens suffered from interaction cycles. XRD and DSC-TG analysis results of Eco-HDCC specimen with preloading stress level of 0.3 after 3 interaction cycles are presented in Fig. 3. Based on the endothermic peak corresponding to the decomposition of Ca(OH)₂ and CaCO₃, the dehydration of Ca(OH)₂ is calculated by the mass loss rate with the temperature range of 400°C ~ 550°C, while the decomposition of CaCO₃ is determined by the mass loss rate with the temperature range of 550°C ~ 950°C (Chai and Xu 2018; Duan et al. 2018). According to the mass loss of Ca(OH)₂ and CaCO₃, the contents can be calculated. Thus the carbonation front of Eco-HDCC was determined.

The carbonation front of Eco-HDCC with different interaction cycle is presented in Fig. 4(a). The carbona-

| Interaction cycle | The depth range from surface of pure moment zone (mm) |
|-------------------|-----------------------------------------------------|
| 0                 | 0–10                                                |
| 5                 | 0–10                                                |
| 10                | 0–10, 10–20                                         |
| 15                | 0–10, 10–20, 20–30                                  |

Fig. 2 Crack in Eco-HDCC specimen: (a) Preloading stress level of 0.7 before interaction cycle; (b) Preloading stress level of 0.7 after 15 interaction cycles; (c) Preloading stress level of 0.5 after 5 interaction cycles; (d) Preloading stress level of 0.5 after 15 interaction cycles.
tion front of Eco-HDCC increases as interaction cycle increases. Besides, the increasing rate of carbonation front is rather intensive when interaction cycles are 1 ~ 5 and the increasing rate will be decreased when interaction cycles are 10 ~ 15. Because the chemical reactions consume lots of Ca(OH)\textsubscript{2} during the initial carbonation process, and the carbonation speed is faster after 1 ~ 5 interaction cycles.

The carbonation front of Eco-HDCC with different preloading stress level is presented in Fig. 4(b). Carbonation front of Eco-HDCC shows an increasing trend with the increase of preloading stress level, and the increasing rate of carbonation front is more obvious when interaction cycle exceeds 5. With the increase of preloading stress level, internal defects in Eco-HDCC specimen increase, especially for preloading stress level of 0.5 and 0.7. For Eco-HDCC with preloading stress level of 0.5, crack occurs in specimen with 5 interaction cycles, and crack width increases with the increase of interaction cycle. Crack can provide path for further migration of CO\textsubscript{2}, thus the increasing rate of carbonation front increases suddenly as the number of interaction cycle is more than 5. For Eco-HDCC with preloading stress level of 0.7, crack worsens during interaction test process. The crack width of Eco-HDCC is larger as preloading stress level increases, thus the ingress speed of CO\textsubscript{2} is faster, resulting in a larger carbonation front.

### 3.3 Pore structure

The pore structure of Eco-HDCC without preloading subjected to different interaction cycles are shown in Fig. 5. For the same depth range of 0 ~ 10 mm, the critical aperture of Eco-HDCC subjected to interaction cycles of 5, 10 and 15 has little change, while the most probable aperture shows an increasing trend with the increase of interaction cycle. For the same depth range of 10 ~ 20 mm, the critical aperture and most probable aperture of Eco-HDCC exposed to 10 interaction cycles are lower than those of Eco-HDCC exposed to 15 interaction cycles. For interaction cycle of 15, both critical aperture and most probable aperture of Eco-HDCC decrease as depth increases. Thus, conclusions can be drawn out that interaction cycles can deteriorate the pore structure of Eco-HDCC specimen, and the deterioration degree of pores decreases as depth deeper.

According to the aperture division principle, pores inside the cementitious composites can be divided into harmless pores (aperture smaller than 20 nm), less harmful pores (aperture range from 20 nm to 50 nm), harmful pores (aperture range from 50 nm to 200 nm) and more harmful pores (aperture larger than 200 nm) (Shen et al. 2018). For the same depth range of 0 ~ 10 mm, harmless pores in Eco-HDCC gradually disappear.
with the increase of interaction cycle, while both harmful pores and more harmful pores in Eco-HDCC show an increasing trend. For the same depth range of 10 ~ 20 mm, harmful pores in Eco-HDCC increases obviously as interaction cycle increases. For interaction cycle of 15, harmless pores in Eco-HDCC increase as depth increases, while harmful pores in Eco-HDCC decreases. Thus, interaction cycle leads to the increase of harmful pores and more harmful pores in Eco-HDCC, and the deterioration degree of pores decreases as depth increases.

Combining the pore size distribution analysis with the change trend of pore characteristic parameters for Eco-HDCC exposed to interaction cycles, it is clear that some small pores deteriorate and become big pores. As a result, harmless pores reduce, and harmful pores increase, which may decrease the ultimate flexural strength and ultimate deflection of Eco-HDCC.

3.4 Flexural property

(1) Interaction cycle

Flexural load-deflection relationships of Eco-HDCC subjected to different interaction cycles are presented in Fig. 6. All flexural load-deflection curves of Eco-HDCC exhibit four stages: linear elastic, non-linear, deflection hardening and deflection softening stage. The flexural curve trends of Eco-HDCC can be described as follows, load-deflection relationship is linear elastic at initial stage. Then internal micro-cracks in Eco-HDCC occur during the process of flexural loading, and the damage is unrecoverable resulting in a nonlinear relationship. In addition, first cracking point forms with the accumulation of internal damages. The matrix of Eco-HDCC cracks with the increase of flexural load, while the flexural load increases gradually due to the fiber bridging capacity, thus the flexural response curve displays characteristic of deflection hardening. Moreover, failure localizes as more fibers pull out or rupture in Eco-HDCC during the process of flexural loading, and major crack forms, so the flexural property curve of Eco-HDCC shows a deflection softening behavior with a characteristic of flexural load decrease.

The ascending curve slope of flexural response for Eco-HDCC exposed to 0 ~ 5 cycles are steeper than those exposed to 10 ~ 15 cycles, as shown in Fig. 6. The length of deflection hardening stage for Eco-HDCC shows a decreasing trend as interaction cycle increases. As interaction cycle increases, pore structure deteriorates and damage accumulates, resulting in loose structure of matrix. Besides, the volume of water increases as water turns into ice, and expansion force can be caused. The volume reduces as ice turns into water, and expansion force can be released. Fibers bear tensile load to prevent the increase of pore volume during freeze process of Eco-HDCC, and the tensile stress of fibers will be re-

![Fig. 5 Pore size distribution of Eco-HDCC exposed to different interaction cycle: (a) Cumulative intrusion volume curve; (b) Log differential intrusion volume curve; (c) Critical aperture and most probable aperture; (d) Porosity.](image-url)
leased due to the volume decreases during thaw process of Eco-HDCC. Fibers are subjected to repeat tensile stress during freeze-thaw process of Eco-HDCC, and fiber surfaces are scratched with several stripes because its stiffness is lower than that of surrounding matrix. Thus, fibers in Eco-HDCC specimen damage during the process of freeze-thaw cycles, which can reduce the fiber bridging capacity. In summary, the matrix and fiber will worsen as interaction cycle increases. Therefore, Eco-HDCC specimen stiffness decreases with the increase of interaction cycle, and slope of ascending curve decreases. In addition, fiber bridging capacity decreases as interaction cycle increases, so the length of deflection hardening for Eco-HDCC decreases.

Interactive effect on flexural property of Eco-HDCC is summarized in Table 4. Ultimate flexural strength of Eco-HDCC shows a decrease trend as interaction cycle increases, and the decrease rate can reach 19% ~ 32% for interaction cycles of 15, while ultimate flexural strength changes little when Eco-HDCC is subjected to interaction cycles of 3 ~ 5. As interaction cycle increases, pore structure deteriorates resulting in the decrease of ultimate flexural strength. The pore structure analysis has been described in the Pore structure section. It takes about 8 days for per interaction cycle of Eco-HDCC. When the interaction cycles are 3, 5, 10 and 15, the test period are 24, 40, 80, 120 days. And the interaction test period is all beyond the initial curing time ages of 28 days. The hydration speed of cement in Eco-HDCC is very fast during the initial curing time ages of 28 days, and the un-hydrated cement particles are normally still present in hardened Eco-HDCC specimen, so the hydration of un-hydrated cement in water forms hydration product. Besides, the reaction degree of fly ash in paste increases rapidly at the first month beyond the curing ages of 28 days, and then the increasing rate slows down at later age (Zhang et al. 2017; Huang and Ye 2015). This can be attributed to the fact that most Ca(OH)₂ has already been consumed by the pozzolanic reaction of fly ash and carbonation reaction. In addition, the pozzolanic reaction and carbonation reaction are slower with the increase of interaction cycle, resulting in a lower ultimate flexural strength of Eco-HDCC. According to the existing research results (Zhang et al. 2017; Huang and Ye 2015), the pozzolanic reaction speed of fly ash in Eco-HDCC after 3 interaction cycles is slightly faster than that of fly ash in Eco-HDCC after 5 interaction cycles. Eco-HDCC is damaged more seriously for the interaction cycles of 5. Thus the comprehensive effect makes a result that the ultimate flexural strength of Eco-HDCC has little change during the interaction process of 3 ~ 5 cycles.

Fig. 6 Flexural response of Eco-HDCC subjected to different interaction cycle: (a) Un-preloading; (b) Preloading stress level of 0.3; (c) Preloading stress level of 0.5; (d) Preloading stress level of 0.7.
Ultimate deflection of Eco-HDCC also shows a decrease trend as interaction cycle increases, and the decrease rate can reach 24% ~ 50% for interaction cycles of 15, as listed in Table 4. Matrix structure is loose and fiber property worsens when Eco-HDCC is subjected to interaction cycle. After the interaction cycle, several stripes on the surface of fiber are observed before the tensile test, resulting in a poor fiber bridging effect (Chai and Xu 2018). According to the design theory of Eco-HDCC material, a poor fiber bridging effect may lead to a lower tensile deformation. The bottom of Eco-HDCC specimen bears flexural-tensile load during the process of flexural loading. Thus, the ultimate flexural deflection deformation capacity may decrease as the increase of interaction cycle.

According to bridge structure code, ultimate deflection of bridge deck is a key indicator in design of bridge engineering. So the flexural property curve for bridge design should be chosen with reference to the lowest ultimate deflection principle. Besides, tensile property with first cracking point is chosen to be the design value of Eco-HDCC material (Michael and Li 2009; Kim et al. 2004). Thus, the flexural property of Eco-HDCC with first cracking point is used in design of bridge deck slab. The stress level for first cracking point is 0.5. For the purpose of safety, when Eco-HDCC is subjected to 15 interaction cycles, flexural property of Eco-HDCC with preloading stress level of 0.5 is selected for bridge design.

(2) Preloading stress level
Flexural load-deflection relationships of Eco-HDCC with different preloading stress level are presented in Fig. 7. All flexural property curves contain four stages: linear elastic, nonlinear, deflection hardening and deflection softening stage. These characteristics are independent on preloading stress level. Besides, ascending curve slopes of flexural response for Eco-HDCC with preloading stress levels of 0 and 0.3 are steeper than those for Eco-HDCC with preloading stress levels of 0.5 and 0.7. In addition, the lengths of deflection hardening stage for Eco-HDCC with preloading stress levels of 0.5 and 0.7 are lower than those for Eco-HDCC with preloading stress levels of 0 and 0.3. Internal damages exist in Eco-HDCC with preloading stress level of 0.5 and 0.7, the damages deteriorate during the process of flexural loading, which can weak the stiffness of specimen. Thus the slopes of ascending curves for Eco-HDCC with higher preloading stress level are lower. Fibers in Eco-HDCC bear tensile stress during the process of flexural loading, and several fibers pull out or rupture when preloading stress level is higher, thus fibers damage more severely in Eco-HDCC with higher preloading stress level. The matrix strength also damages more seriously. Therefore, the ultimate deflection deformation capacity decreases for Eco-HDCC with higher preloading stress level, resulting in a shorter length of deflection hardening stage.

Both ultimate flexural strength and ultimate deflection of Eco-HDCC decrease as preloading stress level increases, while flexural properties of Eco-HDCC with preloading stress levels of 0 and 0.3 have minor differences. Flexural performance of Eco-HDCC with different preloading stress level is related to preloading damage degree.

The ultimate flexural strength of Eco-HDCC with different preloading stress level has little changes when interaction cycles are 1 ~ 5, and ultimate flexural strength of Eco-HDCC with preloading stress level of 0.5 and 0.7 obviously decrease when interaction cycles are 10 ~ 15,

| Preloading stress level | Number of interaction cycle | Ultimate flexural strength (MPa) | Reduced amplitude of ultimate flexural strength (%) | Ultimate deflection (mm) | Reduced amplitude of ultimate deflection (%) |
|-------------------------|-----------------------------|--------------------------------|-------------------------------------------------|--------------------------|---------------------------------------------|
| 0                       | 1                           | 14.31                          | -                                               | 2.70                     | 2.9                                         |
|                         | 3                           | 13.60                          | 4.6                                             | 2.64                     | 14.7                                        |
|                         | 5                           | 12.69                          | 11.3                                            | 2.32                     | 17.3                                        |
|                         | 10                          | 11.79                          | 13.6                                            | 2.25                     | 21.3                                        |
|                         | 15                          | 11.55                          | 17.6                                            | 2.07                     | 23.9                                        |
| 0.3                     | 1                           | 13.74                          | -                                               | 2.61                     | 10.3                                        |
|                         | 3                           | 12.51                          | -                                               | 2.44                     | 20.3                                        |
|                         | 5                           | 12.03                          | -                                               | 2.37                     | 20.3                                        |
|                         | 10                          | 12.15                          | -                                               | 2.15                     | 20.3                                        |
|                         | 15                          | 11.52                          | -                                               | 2.05                     | 24.1                                        |
| 0.5                     | 1                           | 13.41                          | -                                               | 2.57                     | 2.9                                         |
|                         | 3                           | 12.06                          | -                                               | 2.18                     | 19.9                                        |
|                         | 5                           | 12.51                          | -                                               | 2.11                     | 22.4                                        |
|                         | 10                          | 11.67                          | -                                               | 2.06                     | 24.3                                        |
|                         | 15                          | 11.01                          | -                                               | 1.83                     | 32.2                                        |
| 0.7                     | 1                           | 13.17                          | -                                               | 2.27                     | 16.5                                        |
|                         | 3                           | 12.33                          | -                                               | 1.90                     | 30.1                                        |
|                         | 5                           | 12.36                          | -                                               | 1.42                     | 47.8                                        |
|                         | 10                          | 10.50                          | -                                               | 1.71                     | 37.1                                        |
|                         | 15                          | 9.63                           | -                                               | 1.36                     | 49.6                                        |

Table 4 Flexural property of Eco-HDCC subjected to different interaction cycle.
as shown in Table 4. Carbonation speeds of Eco-HDCC with 1 ~ 5 interaction cycles are faster than those with 10 ~ 15 interaction cycles. And carbonation reaction can make Eco-HDCC matrix denser, improving the ultimate flexural strength. Besides, carbonation fronts of Eco-HDCC with preloading stress levels of 0.5 and 0.7 are deeper than those of Eco-HDCC with preloading stress levels of 0 and 0.3. In addition, hydration reaction and pozzolanic reaction also occur during the interaction process. The crack induced by preloading may offer paths for water, resulting in a faster speed for hydration and pozzolanic reactions. Therefore, considering carbonation, hydration and pozzolanic reactions, a minor difference on ultimate flexural strength can be observed for Eco-HDCC with 1 ~ 5 interaction cycles Eco-HDCC specimens with preloading stress levels of 0.5 and 0.7 exist cracks when interaction cycles are 10 ~ 15, and crack width worsens as interaction cycle increases. Moreover, the existing cracks in Eco-HDCC specimens deteriorate during the process of flexural loading, resulting in an obvious decrease of ultimate flexural strength for Eco-HDCC with preloading stress levels of

![Graphs showing load vs. deflection for different interaction cycles and preloading stress levels.](image-url)

Fig. 7 Flexural response of Eco-HDCC with different preloading stress level: (a) 1 interaction cycle; (b) 3 interaction cycles; (c) 5 interaction cycles; (d) 10 interaction cycles; (e) 15 interaction cycles.
0.5 and 0.7.

Ultimate deflection of Eco-HDCC shows a decrease trend as preloading stress level increases, and the decrease degree of ultimate deflection is larger than that of ultimate flexural strength, as listed in Table 4. It is illustrated a phenomenon that interaction cycle has an obvious effect on ultimate deflection rather than on ultimate flexural strength. Preloading stress level has a negative effect on fiber and matrix properties. Fiber and matrix strength decrease more obviously with higher preloading stress level. Thus, ultimate deflection deformation capacity decreases as preloading stress level increases.

3.5 Flexural toughness

Flexural toughness of Eco-HDCC can be defined as the area under load-deflection curve, and the deflection coordinate range is from zero to peak load point. Flexural toughness is a key indicator to reflect the energy consumption in zone subjected to dynamic load (Ngo and Kim 2018; Ghadban et al. 2018; Sukontasukkul et al. 2018). The flexural toughness of Eco-HDCC is presented in Fig. 8. It can be seen that flexural toughness of Eco-HDCC shows a decrease trend as interaction cycle increases. Notably, when Eco-HDCC is preloaded with stress levels of 0 and 0.3, flexural toughness of Eco-HDCC with 1 interaction cycle is higher than that of Eco-HDCC without interaction cycle. Eco-HDCC specimens have little damages when preloaded with stress levels of 0 and 0.3. Besides, carbonation, hydration and pozzolanic reactions may contribute to make the matrix structure denser, which can increase the ultimate flexural strength. Thus, the flexural toughness is higher for Eco-HDCC with preloading stress levels of 0 and 0.3 when interaction cycle is 1. As interaction cycle increases, matrix and fiber properties deteriorate, resulting in the decrease of ultimate flexural strength and ultimate deflection. Thus, the flexural toughness of Eco-HDCC shows a decrease trend as interaction cycle increases.

4. Conclusions

In the study, flexural properties of Eco-HDCC for bridge deck link slab exposed to interaction of freeze-thaw cycle and carbonation were investigated. Preloading stress level on flexural property of Eco-HDCC was considered. In addition, carbonation front and pore structure of Eco-HDCC subjected to interaction cycles were discussed. For safety consideration, flexural properties of Eco-HDCC with 15 interaction cycles and preloading stress level of 0.5 can be adopted for bridge deck link slab design. And some main conclusions can be drawn as follows:

1. There is no crack in Eco-HDCC specimen with preloading stress levels of 0 and 0.3 subjected to interaction cycle. Besides, Eco-HDCC specimen with preloading stress level of 0.5 cracks after 5 interaction cycles, and preloading stress level of 0.7 can induce crack in Eco-HDCC specimen before interaction cycles. Crack width of Eco-HDCC specimen increases as interaction cycle increases.

2. Carbonation front of Eco-HDCC increases when interaction cycle or preloading stress level increases. Carbonation speeds of Eco-HDCC with 1 ~ 5 interaction cycles are higher than those of Eco-HDCC with 10 ~ 15 interaction cycles. In addition, carbonation speeds of Eco-HDCC with preloading stress levels of 0.5 and 0.7 are higher than those with preloading stress levels of 0 and 0.3.

3. As interaction cycle increases, harmless pores reduce while harmful pores and more harmful pores increase with same depth range in Eco-HDCC specimen. Besides, the deterioration degree of pore structure decreases as depth increases.

4. Flexural load-deflection curves of Eco-HDCC exhibit four stages: linear elastic, non-linear, deflection hardening and deflection softening stage. The ascending curve slopes of flexural response for Eco-HDCC exposed to 0 ~ 5 cycles are steeper than those exposed to 10 ~ 15 cycles. In addition, ascending curve slopes of Eco-HDCC with preloading stress levels of 0 and 0.3 are steeper than those with preloading stress levels of 0.5 and 0.7.

5. In general, ultimate flexural strength and ultimate deflection of Eco-HDCC decrease as interaction cycle increases. In addition, higher preloading stress level leads to lower ultimate flexural strength and ultimate deflection.

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