Proceedings of the Fifth International Workshop on Seawater Sea-Sand Concrete (SSC) Structures Reinforced with FRP Composites

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15-16 January 2022, Online, Hong Kong, China

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PREFACE

Concrete structures in coastal/marine environments are subject to deterioration due to the corrosion of steel reinforcement, resulting in considerable direct economic loss as well as indirect environmental burden. To enhance the durability of the concrete structures in such environments, the use of fibre-reinforced polymer (FRP) reinforcement, which is expected to be little affected by chloride ions, to replace steel reinforcement in concrete structures has attracted significant attention and is gaining increasing acceptance. The application of FRP in concrete structures opens a new avenue for concrete production with the direct use of locally available seawater and sea-sand for marine infrastructure, resulting in the FRP-reinforced seawater sea-sand concrete (FRP-SSC) structures, which offer compelling economic and environmental advantages through savings in freshwater and material transportation cost as well as reduced rive-sand mining. The bright prospects of FRP-SSC structures in the development of sustainable civil infrastructure have kindled growing research interests on relevant topics among researchers worldwide.

In this context, the FRP-SSC Structures Workshop series was initiated, with the First Workshop held in December 2016 at The Hong Kong Polytechnic University (PolyU), Hong Kong, China, and has now become an annual event. The Second FRP-SSC Workshop was held at PolyU in 2018, together with the launching ceremony of a major multi-disciplinary project funded by the Theme-based Research Scheme (TRS) of the Hong Kong Research Grants Council. The major project aims to develop FRP-SSC structures for marine infrastructure with a total budget of over HK$52 million. The Third FRP-SSC Workshop, jointly organised by PolyU and the Southern University of Science and Technology (SUSTech), was successfully held in January 2020 at the SUSTech campus, Shenzhen, China. The Fourth FRP-SSC Workshop held online in January 2021 hosted over 700 attendees.

The Fifth FRP-SSC Structures Workshop was held online on 15-16 January 2022. To enhance awareness of the emerging technology among the relevant industries, the Workshop included an industry session which was held on the morning of 15 January 2022, with a focus on the practical applications of FRP in civil engineering structures. This was followed by three half-day research sessions, which included invited talks on recent scientific progress and technological advances on FRP, seawater sea-sand concrete, and related topics. The two-day Workshop included 24 invited presentations and attracted over 700 registrants, among which over 150 participants were from the industry.

On behalf of the Organizing Committee, I would like to thank all invited speakers for sharing their insights regarding the applications of FRP-SSC structures and the recent scientific progress on related topics at the Workshop. I would also like to thank all attendees for their participation. Specially, my thanks go to Dr. Botong ZHENG and the members of the Workshop Secretariat, who provided the secretarial support, covering technical, logistics and other necessary aspects. The support from the Sponsor, Fibrpro International Limited, is gratefully acknowledged and is highly appreciated.

Tao YU (Workshop Chair)

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PRACTICAL APPLICATIONS OF FRP BARS IN REINFORCING CONCRETE STRUCTURES IN CANADA AND BEYOND

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ABSTRACT
Corrosion of steel reinforcing bars stands out as a significant factor limiting the life expectancy of reinforced concrete infrastructure worldwide. In North America in particular, the corrosion of steel reinforcement in concrete bridges subjected to deicing salts and/or aggressive environments constitutes the major cause of structure deterioration, leading to costly repairs and rehabilitation as well as a significant reduction in service life. An effective solution to this problem is the use of corrosion-resistant materials, such as high-performance fiber-reinforced polymer (FRP) composites. The applications of FRP reinforcement in the last 25 years have been approved, and this cutting-edge technology has emerged as one of the most cost-effective alternatives to traditional solutions. The number of concrete structures reinforced with FRP bars has been growing to overcome the problems commonly caused by the corrosion of steel reinforcement. The objective of this keynote is to show that FRP bar is on its way to gaining widespread acceptance worldwide. Clearly, the most tangible successes are reinforced-concrete highway bridges, parking garages, tunneling, and marine structures, in which corrosion resistance and installation flexibility are major assets. Additionally, this keynote highlights the developments and advances in FRP reinforcements for sustainable and resilient concrete structures including Glass FRP (GFRP), Carbon FRP (CFRP) and Basalt FRP (BFRP) straight and bent rebars using innovative techniques and materials as well as the development of new editions of design codes and specifications for FRP bars.

HYDRATION KINETICS AND MECHANICAL PROPERTIES OF SEAWATER-MIXED CEMENT PASTES: DISCUSSION FROM SINGLE CLINKER PHASES TO CEMENT PASTE

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ABSTRACT
In recent years, increasing attention has been paid to the possible use of seawater for concrete production due to the shortage of freshwater, particularly in remote islands and for the construction of offshore structures. However, cement and seawater are complex systems containing many minerals and ions. In order to have a basic understanding of the main hydration reactions and hydration mechanisms of seawater-mixed cement pastes, single phases contained in the cement clinker are usually first studied. In this work, the effects of seawater on the hydration and hardening properties of tricalcium silicate (C_3S) and tricalcium aluminate (C_3A) were explored because these two single phases are known to have a more significant contribution to the hydration reactions at the early ages. The results also showed that seawater accelerated the early hydration of C_3S and C_3A. That would lead to faster setting, higher loss of workability and higher early-age compressive strength. However, the lower later-age compressive strength development might be ascribed to the deterioration effect of the seawater ions on C-S-H gel and the retardation effect of seawater on C_3A hydration at later ages.

KEYWORDS
Kinetics, mechanical properties, durability, seawater, cement.

SEAWATER AND SEA SAND ULTRA-HIGH PERFORMANCE CONCRETE UTILISING HIGH VOLUME SUPPLEMENTARY CEMENTITIOUS MATERIALS

Xiao-Ling Zhao[1*], Shameer Saleh[1] and Aziz Hasan Mahmood[1]
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EXTENDED ABSTRACT
To offset the carbon footprint and the enormous consumption of natural resources, such as river sand and potable water in manufacturing concrete (Xiao et al. 2017), the utilization of alternative sustainable sources of binders and fillers need to be explored. This paper presents the summary of an ongoing experimental investigation on the possibility of incorporating marine resources (i.e., seawater and sea sand) as well as industrial by-products (i.e., ground granulated blast furnace slag and silica fume) as supplementary cementitious materials (SCMs) in ultra-high-performance concrete (UHPC) fabrication. Twelve mixes were developed by substituting cement with SCMs at various proportions (25%, 37.5%, 50% and 62.5% by mass), utilising non-conventional aggregates (natural sea sand, river sand and washed beach sand) and varying water to total binder ratio (0.15, 0.2, 0.25). The physical, mechanical and dimensional stability characteristics of the mixes were analysed based on their unit weight, workability, compressive strength development and long-term drying and autogenous shrinkage.

Results reveal that the incorporation of seawater and sea sand in UHPC affects workability marginally. The presence of silica fume improves the workability owing to its spherical shaped particles while the angular slag particles slightly reduce the workability. Characteristic compressive strength at 28 days of at least 110 MPa can be achieved with up to 62.5% cement replacement. Marine UHPC maintains slightly higher compressive strength for up to 28 days, however, the rate of long-term strength development decelerates with the leaching of soft hydration products. As demonstrated in Fig. 1, ordinary Portland cement (OPC) substitution with SCMs yields significantly lower early-age compressive strength, but a comparable or even higher long-term compressive strength can still be achieved. For instance, a 73.2% decrease in 1-day and 11.9% improvement in 90-day strength was observed from a 62.5% OPC replacement. Curing UHPC in seawater reduces the long-term strength of cement-based UHPC and the early age strength of SCM-incorporated UHPC. However, slag and silica fume incorporated concrete endured smaller strength degradation under seawater curing. The incorporation of SCMs moderately increases autogenous shrinkage but significantly reduces drying shrinkage (11.6% increase of autogenous shrinkage and 22% decrease of drying shrinkage in 50% OPC replaced mix compared to control mix), thereby causing a decrease in the overall shrinkage. Fig. 2 shows the SEM micrographs, where considerably fewer shrinkage cracks were observed in the 50% SCM based mix compared to the control mix. In general, as opposed to conventional UHPC, drying shrinkage was found to be higher in seawater and sea sand UHPC. Based on the experimental analyses, a 50% replacement of OPC by 37.5% ground slag and 12.5% silica fume was found to be optimum for adequate strength gain and workability without increased long-term shrinkage when compared to the control mix.

Extensive experimental investigations are underway to evaluate the durability properties (e.g., transport properties, chemical attack, wetting and drying, etc.) of the UHPC described above and its application in FRP-seawater sea sand concrete hybrid construction which has great potential in marine infrastructure (e.g., Teng et al. 2011; Li et al. 2016; Wang et al. 2017; Benzecry et al. 2021; Dong et al. 2021).

KEYWORDS
Ultra-high-performance concrete; seawater; sea sand; industrial by-products; slag; silica fume.

ACKNOWLEDGEMENTS
This project is sponsored by an Australian Research Council Discovery Grant (DP160100739). The authors thank Randwick Council for their permission to collect seawater and sea sand from Malabar beach in Sydney. SEM was conducted at the Mark Wainwright Analytical Centre at UNSW.

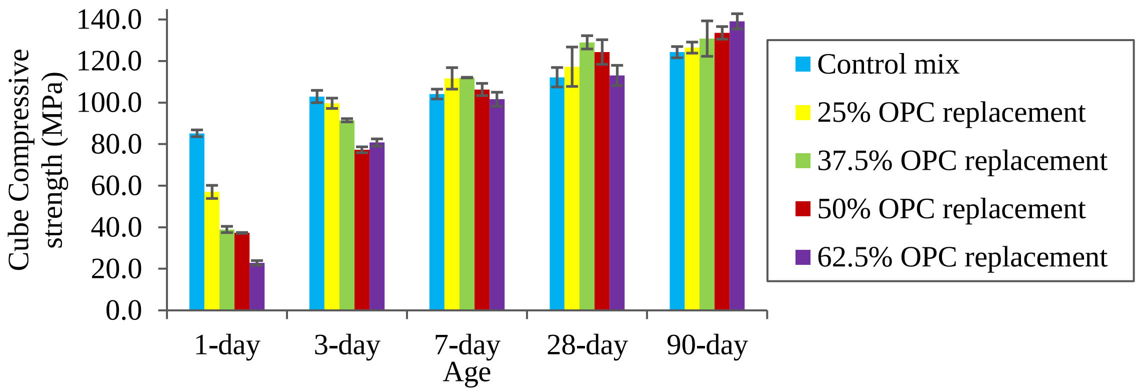
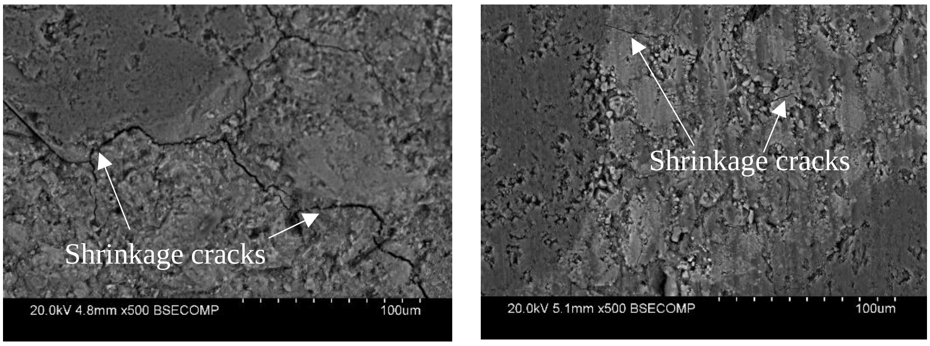


Figure 1. Effect of OPC replacement on compressive strength of marine UHPC



(a) (b)

Figure 2. SEM micrographs of (a) control mix and (b) 50% OPC replaced mix

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WIRELESS OPTICAL FIBRE HUMIDITY SENSOR SYSTEM IN SEAWATER SEA SAND CONCRETE

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EXTENDED ABSTRACT
Relative humidity (RH) is the ratio of the partial pressure of water vapour to the equilibrium vapour pressure of water at the same temperature, thus it can reflect environmental conditions of concrete structures. Water inside the reinforced concrete structures helps to speed up carbonation and corrosion which can reduce significantly the service lifetime of these structures [1]. Marine infrastructures are exposed to highly humid environment, therefore it is essential to monitor the water ingress inside the marine infrastructure for better understanding of the structural integrity as it is one of the key indicators of structural degradation, coupled with the presence of corrosive ions and reduced pH caused by carbonation. Traditional RH sensors include capacitive, or mechanical resonance - based sensors, but they have the disadvantages of large size, long response time and saturation in high RH conditions [2]. To overcome these disadvantages, an optical fibre-based humidity sensor system has been developed jointly by Hong Kong Polytechnic University and City, University of London and has been installed in HKZM Bridge Exposure Site to evaluate their long-term performance.

The wireless optical fibre humidity sensor system includes 4 humidity/temperature sensors cast respectively into 4 different concrete slabs, a fibre Bragg grating (FBG) interrogator, Raspberry Pi with LTE Module, UPS, PVC cabinet. Each humidity/temperature sensor includes two FBGs inscribed into the same fibre, with one FBG coated with polyimide (PI) as the active element for relative humidity (RH)/temperature sensing and the other FBG without coating for temperature measurement and for temperature compensation.

The data collected by the sensor interrogator are uploaded to a cloud server with LTE Module which can be accessed remotely via a user-friendly interface. *Figure 1* shows the temperature data from the 4 optical fibre humidity sensors which are installed at HKZM Exposure Site and *Figure 2* shows the humidity data from these 4 sensors. These data were obtained during 1 October 2021 to 15 November 2021, and it is worth pointing out that the sudden drop, of temperature as shown in figure 1 and of humidity in Figure 2 dated 8 November, matches nicely with the meteorological data released by Hong Kong Observatory on the same day. This confirms that the information extracted from the sensor data does reflect truly the environment that the concrete slabs are subjected to.

KEYWORDS
FBG humidity sensor, seawater sea sand concrete, wireless structure health monitoring.

ACKNOWLEDGEMENTS
The authors gratefully acknowledge the financial support provided by the Hong Kong Research Grants Council (T22-502/18-R and PolyU 152634/16E).

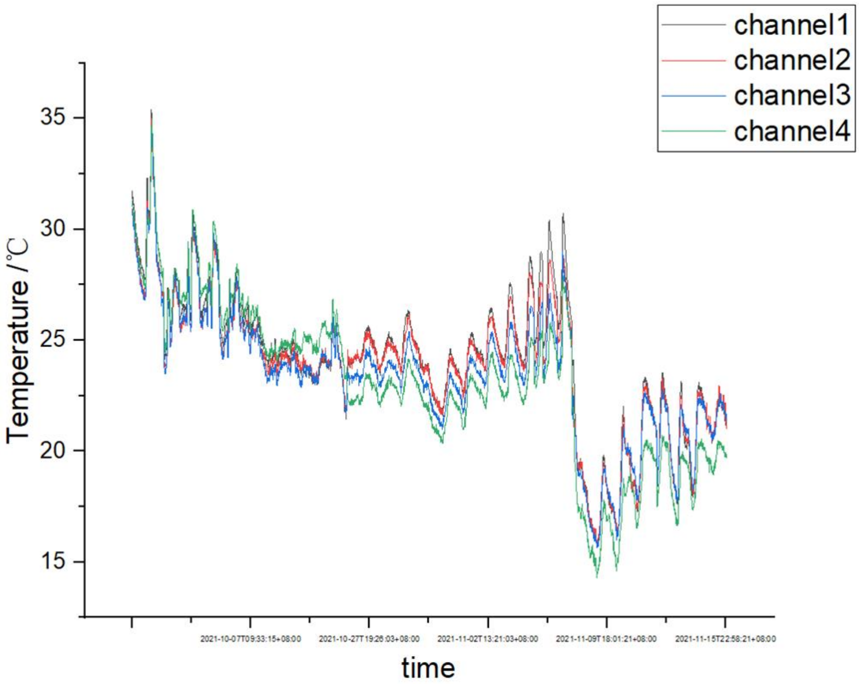

Figure 1 Temperature data from the installed sensors

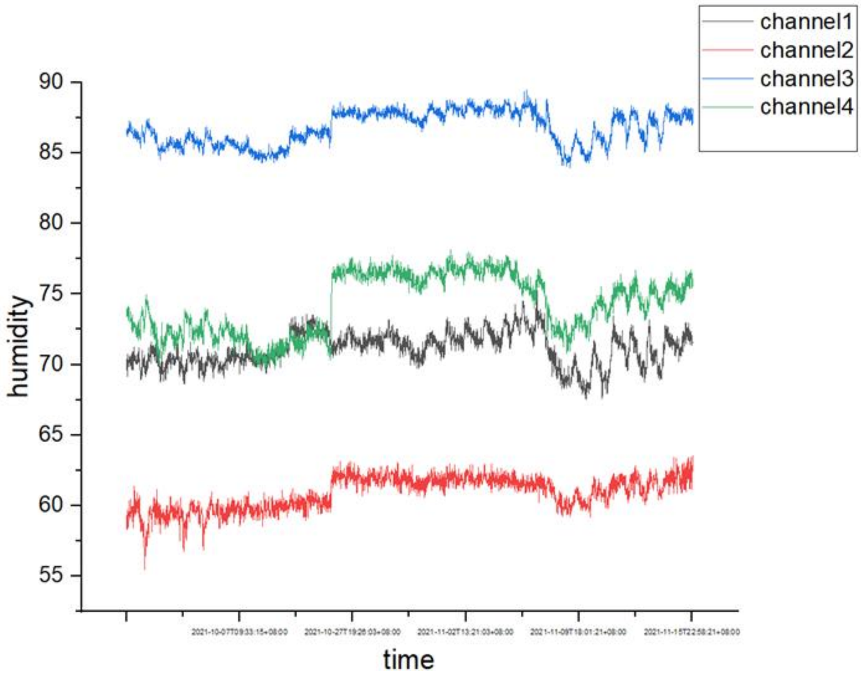

Figure 2 Humidity data from the installed sensors

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EFFECTS OF CEMENTITIOUS COATINGS ON CORROSION PREVENTION OF STEEL REINFORCEMENT IN NORMAL AND ULTRA-HIGH-PERFORMANCE SEAWATER AND SEA SAND CONCRETE

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EXTENDED ABSTRACT

This paper presents a feasibility study of using commonly used cement slurry (CC) and alkali-activated slag (AAS) to coat the steel reinforcement and cast it in a seawater seasand concrete (SSC) matrix. The coatings had a liquid to solid ratio of 0.5, and their thickness around steel reinforcement was maintained between 600 to 800 µm. In order to provide sufficient time for passivation, the coatings were applied seven days before casting steel in SSC. The activator used to prepare AAS coating contained water glass and sodium hydroxide to get a SiO_2/Na_2O ratio of 1. The alkali content was fixed at 5%. The coated steels' protectiveness was compared to control uncoated steel reinforcements (UC) in SSC. Further, two different matrices comprising normal strength (NSSC) and ultra-high-performance seawater sea sand concrete (UHP-SSC) were used to evaluate the influence of the surrounding concrete type. A total of 18 specimens were prepared and tested for electrochemical responses for 56 days and microscopic observations. It was observed that both UC-NSSC showed an active corrosion state during the entire exposure period. However, the UC-UHP-SSC demonstrated significant variations in its corrosion behavior in the fresh and hardened state. The UC-UHP-SSC showed active corrosion in its fresh state, but the corrosion process was inhibited in its hardened state, suggesting that the hardened UHP-SSC effectively prevented corrosion even in chloride mixed concrete due to its dense microstructure. The corrosion susceptibility was significantly reduced for prepassivation of steel reinforcements by cement coatings. However, the effectiveness was dependent on the concrete cover type. For NSSC, the cement coated steel showed an uncertain corrosion state during the exposure period, suggesting the cement coating was ineffective in preventing the chloride ingress. However, in UHP-SSC, the cement coatings inhibited any steel corrosion initiation in fresh and hardened states. For the AAS coatings on steel reinforcements, the corrosion was inhibited entirely irrespective of the matrix type. This was due to a very low ingress of chloride ions into the coating from the surrounding SSC matrix (Figure 2).

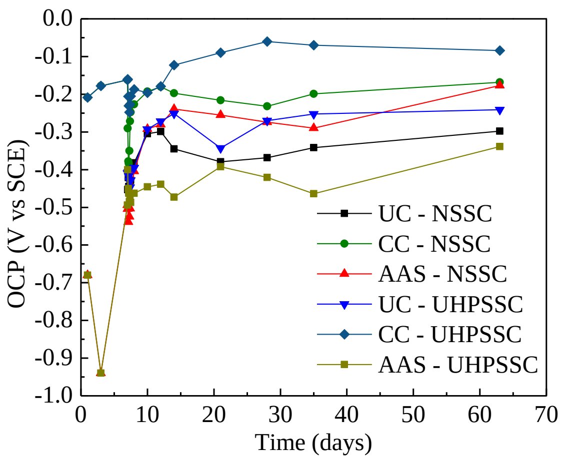

Figure 1. Open circuit potential (OCP) of different steel reinforcements in SSC

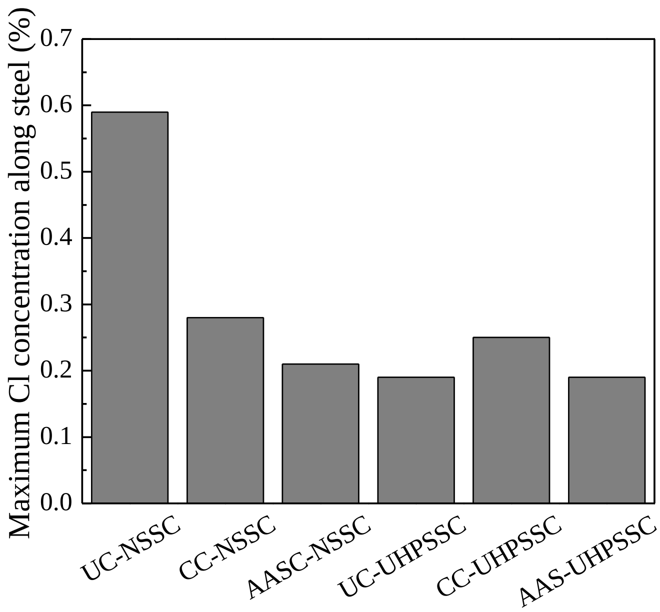

Figure 2. Chloride distribution along steel surface measured using EDS in different samples

KEYWORDS
Corrosion, steel rebar, alkali-activated slag, coating, ultrahigh performance concrete, seawater sea sand concrete.

ACKNOWLEDGEMENTS
The authors would like to thank Guangdong Province R&D Plan for Key Areas (Project code: 2019B111107002) and the Hong Kong Research Grants Council - Theme-based Research Scheme (Project code: T22-5-2/18-R) for the financial support of this research project.

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STUDY ON TRICALCIUM SILICATE HYDRATION AND CALCIUM SILICATE HYDRATE FORMATION USING AB INITIO METHOD

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EXTENDED ABSTRACT
Understanding the hydration mechanisms of tricalcium silicate (C_3S) and formation process of calcium silicate hydrate (C-S-H) is fundamental in concrete technology, which can help the modification of the materials structure of concrete at nano meter scale and subsequently improving the mechanical properties and durability of concrete. In this study, we provide an exhaustive atomic insight into the C_3S hydration and C-S-H formation by first-principles calculations. First, we introduce the background of C_3S hydration and basic characterization of C-S-H. Then, the adsorption mechanism of water on the C_3S surface is revealed from first-principles calculations. Figure 1 shows the adsorption process. We find the adsorption energy increases with the increase of electron transfer at water/C_3S interface and strength of total Ca-Ow bonds. The mechanism of adsorption of water on C_3S surfaces is the electron transfer from valence band maximum (VBM) of C_3S surface to lowest unoccupied molecular orbital (LUMO) of water molecule, raising the Fermi level and shifting the bonding molecular orbital downward. The stability of the dissociative and molecular adsorption is reverse for isolated and bulk water due to the different reaction pathways. Next, we discuss the feasibility of the calcium silicate aqua complexes as C-S-H precursors using ab initio metadynamics simulations. We discover two kinds of calcium silicate aqua complexes, $[Ca(H_2O)n(SiO_2(OH)_2)]$ and $[Ca(H_2O)n(SiO(OH)_3)]^+$, which have six and five stable states on the free energy surface (FES), respectively and different ligand substitution mechanisms. Figure 2 shows Structural analysis of the WT-MetaD simulations for $CaSiO_2(OH)_2$ and $CaOHSiO(OH)_3$ solution systems. Based on results, we further propose a potential formation pathway for C-S-H precursors, where the replacement of water ligands of the central Ca ion by silicate ligands initiates the polymerization of aqueous monomers and promotes the formation of C-S-H precursors. Moreover, an ab initio mechanism for tricalcium silicate dissolution was unraveled. The calcium sites with different coordination environment leads to different reaction pathways and free energy barriers. The low free energy barriers permits the detachment of calcium ions, which is a ligand exchange and auto-catalytic process. Finally, the water adsorption, proton exchange and diffusion of water into the surface layer accelerate the leaching of calcium ions from the surface step by step have been investigated.

KEYWORDS
Tricalcium silicate, hydration, calcium silicate hydrate, first-principles calculations, adsorption, dissolution.

ACKNOWLEDGEMENTS
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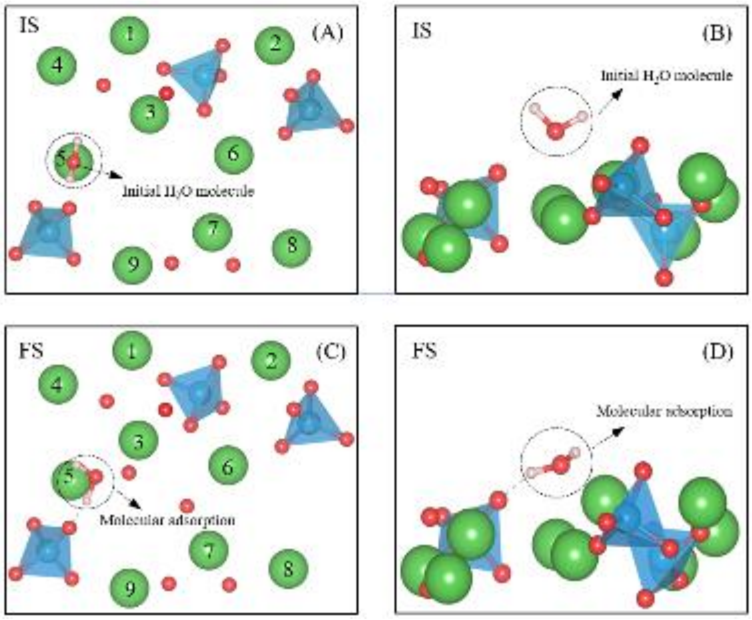

Figure 1. Adsorption process (A) top and (B) side views of initial structures of molecular adsorption on Ca5 site on (011) surface with initially vertical water configuration. (C) top and (D) side views of final structures.

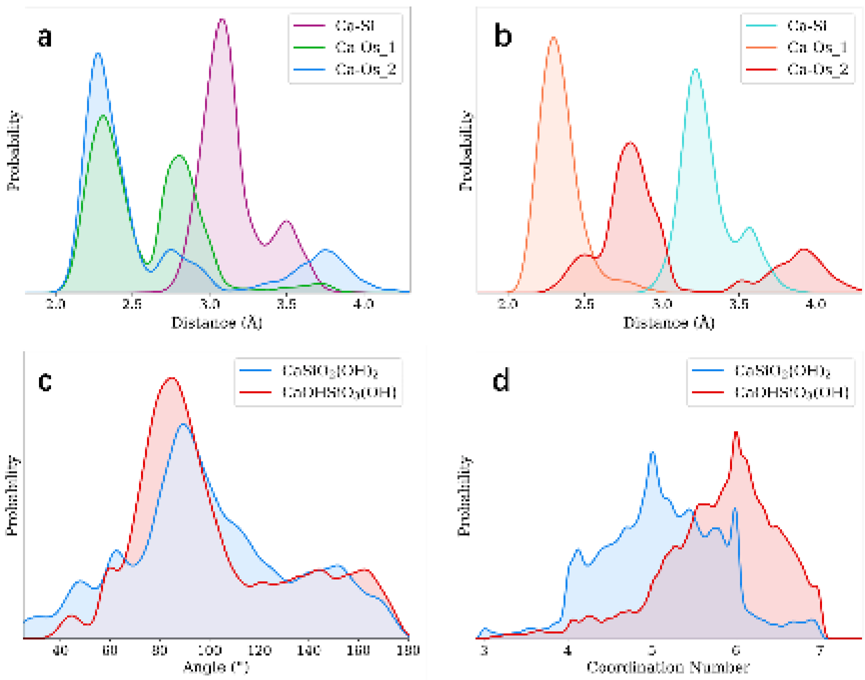

Figure 2. Structural analysis of the WT-MetaD simulations for $CaSiO_2(OH)_2$ and $CaOHSiO(OH)_3$ solution systems. a, b The probability distributions of the distances between the Ca and Si ions as well as the Ca and two Os ions in $CaSiO_2(OH)_2$ and $CaSiO_2(OH)_2$ solution systems, respectively. c The probability distributions of the angles of O-Ca-O with O ions in the first hydration shell of the Ca ion in $CaSiO_2(OH)_2$ and $CaOHSiO(OH)_3$ solution systems, respectively. d The probability distributions of the coordination numbers of Ca ions with O ions in $CaSiO_2(OH)_2$ and $CaOHSiO(OH)_3$ solution systems, respectively.

ATOMISTIC INVESTIGATION ON CHEMICAL REACTION AND SURFACE REACTIVITY OF SILICA UNDER THE ALKALINE ENVIRONMENT

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EXTENDED ABSTRACT

Glass fibre-reinforced polymer (GFRP) composites have become increasingly popular as a durable construction material in civil engineering applications, especially in the application of seawater sea sand concrete (SSC). However, in the long service period of concrete encasement, the alkalinity of cement hydration product is one of the main reasons that lead to the premature failure of GFRP rebar (Won et al. 2008; Won et al. 2012; Wu et al. 2022), also including the reduced the tensile strength and remaining shear strength of GFRP bars (Micelli et al. 2004; Tannous et al. 1999). The current explanation mainly refers to the acceleration of decomposition of Si-O-Si molecular structure of glass fibre under alkaline environment, then the glass fibre is reduced to soluble products, thus damaging the main chain of glass molecules (He et al. 2017). The silica surface under alkaline environment can be probed by different methods from microscopic perspective. The chemical composition changes of the silica surface after alkline interactions can be analyzed using X-ray photoelectron spectroscopy (XPS) or nuclear magnetic resonance (Shchukarev et al. 2004; Sprenger et al. 1990). While all of these surface probing techniques are essential to highlight the consequent changes upon alkaline contact, critical information regarding the structural characteristics and chemical reaction mechanisms is rather difficult to obtain. In recent years, computational modelling with molecular dynamics (MD) simulations has been providing fruitful information to support the findings of experiments and details of the chemical reactions, expanding its versatility from bulk property investigations to surface characterizations at an atomistic resolution.

This paper presents the reactive MD simulations study on the structural and dynamical features of the silica surface under alkaline environment with the application of ReaxFF potential. The atomistic models in this research contains the amorphous silica substrate and the surrounding environment, including pure water environment and saturated sodium hydroxide solution with 54.5 wt% of NaOH (Fig. 1). The model of amorphous silica substrate is produced by the crystalline silica that goes through the melting and quenching simulations. The initial crystalline silica is melted at 5000 K, with a linear temperature ramp from room temperature to 5,000 K over 47 ns under the isothermal-isobaric (NPT) ensemble. The structure is then equilibrated for 10 ns at 5,000 K to make sure the remaining original crystal structure removed completely. The molten silica is then linearly cooled to room temperature of 300 K with a quench rate of 5×10^{12} K/s under NPT ensemble to rapidly solidify the silica substrate. The equilibration and analysis are then conducted to characterize structural and dynamical features of the silica surface under the investigated environmental conditions. The simulation results demonstrate that the hydroxylation mechanism at the surface non-bridging oxygen (NBO) sites (Fig. 2). The investigation on the degradation mechanism of GFRP rebar under alkaline environment is essential for realizing the full potential of the FRP materials.

KEYWORDS

Interfaces, Chemical reaction, Molecular dynamics, Ions, Sodium, Hydroxyl, Amorphous silica.

ACKNOWLEDGEMENTS

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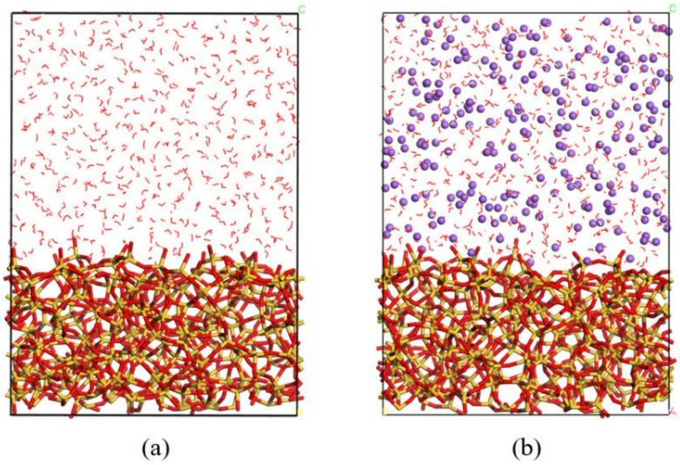

Figure 1. Snapshots of the simulation box with silica substrate under (a) pure water and (b) alkaline environment. Color legend: Na (purple), Si (yellow), O_{glass} (red), O_{water} (red), H (white).

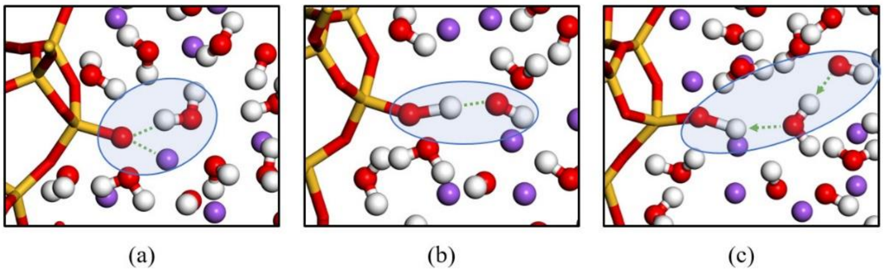

Figure 2. Hydroxylation mechanism at the surface non-bridging oxygen sites. (a) the formation of SiO−Na and $SiO^{-}\cdots H_2O$ of the silica surface; (b) the formation of silanol; (c) the neutralization of OH^{-} by proton donation from adjacent water molecules. Color legend: Blue cricle highlight the reacted atoms; Na (purple), Si (yellow), Oglass (red), Owater (red), H (white).

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REBUILDING CONCRETE

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EXTENDED ABSTRACT
The last several decades have seen many innovations and scientific advances in cement and concrete owing to increasing requirements for higher performance, reduced environmental impact, and an ever-increasing need to achieve solutions that meet societal demand in a sustainable manner. Nano-engineering has emerged as a promising way to improve the properties of concrete by changing the concrete matrix at the nano levels. The use of nanomaterials can offer significant benefits for a variety of applications, ranging from more durable to self-sensing and self-cleaning concrete (Sanchez et al. 2010). Molecular dynamics provides a tool for *in-silico* experimentation in the design of cement-based composites with unique characteristics. Molecular dynamics has given new insights into the structure of the main building block of concrete and has offered new possibilities to study the interaction of water and solutes with solid phases and the bonding mechanisms in reinforced concrete. Lately, additive manufacturing (i.e., 3D printing) is appearing as a new promising avenue for concrete and the construction industry and might possibly become a transformative technology of the 21st century (Khan et al. 2020). 3D printing provides construction speed, design flexibility, and architectural freedom, and enables the creation of a hierarchy of structures and patterns (Figure 1).

The presentation will provide an overview of the research performed in the Multiscale Materials Performance Laboratory at Vanderbilt University in the areas of nano-engineering, chemo-mechanical behavior, and 3D printing of cement-based materials and will discuss the challenges and opportunities of these methods to advance the technology of seawater sea sand concrete.

Figure 1. 3D printing of architectured cement-based materials
[Courtesy of M. Kosson and F. Sanchez, Vanderbilt University, 2021]

KEYWORDS
Nanomaterials, 3D printing, cement-based materials, molecular dynamics.

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THOUGHTS ON THE DURABILITY OF SEAWATER-MIXED CONCRETE

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EXTENDED ABSTRACT
An extensive amount of research has been performed on seawater and sea-sand concrete in recent years and the complex effects of seawater on hydration and microstructural development are well understood (Xiao et al. 2017; Dhondy et al. 2019; Li et al. 2021; Zhao et al. 2021). However, only limited information is available on the long-term durability of seawater-mixed concrete. In this work, we review existing durability literature on seawater-mixed concrete and combine findings with what is known about seawater-induced changes in pore solution, pore structure, and hydration products to identify potential durability concerns of seawater-mixed concrete (Figure 1, Ebead et al. 2022). Seawater accelerates initial hydration, however, its effects on later-age hydration and mechanical properties are typically limited. Studies typically show that at later-ages, seawater has a limited effect in refining the pore structure. Seawater increases the concentrations of chloride, sodium, and other ions, and therefore, the pore solution is more concentrated in seawater-mixed concrete. These ions are also incorporated into hydration products, which are otherwise not changed, except for the formation of Friedel's salt. One of the most important factors controlling concrete durability is the ingress of fluid into concrete. Because the pore structure is not significantly modified, it is not expected that fluid ingress in seawater-mixed concrete is greatly different that in conventional concrete. However, systematic studies comparing ingress of various fluids into seawater-mixed concrete and conventional concrete are missing.

Both drying and autogenous shrinkage are known to increase in seawater-mixed concrete, with a complex dependence on water-to-cement ratio and supplementary cementitious materials (SCMs). The increased shrinkage is due to the refined pore structure and the more ionic pore solution. If used in environments where shrinkage is a concern, then appropriate measures to mitigate both drying and autogenous shrinkage should be considered. The high-concentrations of chloride in the seawater mean that corrosion would be a major concern if conventional steel reinforcement was used in seawater-mixed concrete. Corrosion has long been a major limiter to the use of seawater-mixed concrete and must be carefully tackled. Corrosion could be avoided by using seawater-mixed concrete in non-reinforced applications, using ultra-high-performance concrete, or by using stainless steel/fiber reinforced polymer reinforcement. Only limited number of studies exist on sulfate attack, alkali-silica reaction (ASR), and carbonation; further studies are warranted. As the overall aluminate content in seawater-mixed systems is not modified, it is not expected that seawater-mixed concrete would show greatly different susceptibility to sulfate attack than conventional concrete. Results from literature are inconclusive and understanding the interactions between sulfates and chlorides is key to predicting sulfate attack resistance in seawater-mixed concrete systems. Because the pore solution alkali and hydroxide contents are increased, ASR expansion could be worsened, although it is unclear if this is a major issue in coastal construction. Regardless, appropriate use of SCMs will mitigate both sulfate attack and ASR. It does not appear that the carbonation process is significantly affected by the use of seawater, although some studies have found reduced carbonation in seawater-mixed concrete.

While it is best to do case-by-case analysis of durability concerns, results from literature do not suggest major durability issues will occur with seawater-mixed concrete, especially when used with appropriate amounts of SCMs in concrete that is unreinforced or reinforced with non-corrosive reinforcement.

KEYWORDS
Seawater, durability, review, chloride.

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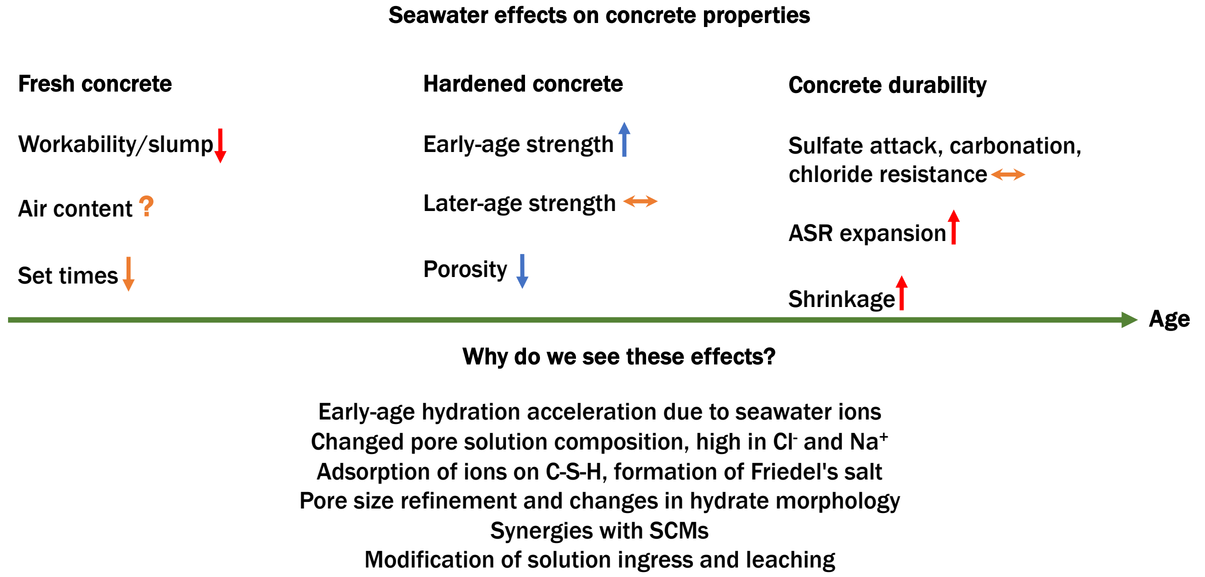

Figure 1. Summary of micro- and macro-scale effects of seawater on concrete properties (Ebead et al. 2022).

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MEASURE MODULUS OF ELASTICITY OF STANDARD CONCRETE CUBES USING SURFACE-BONDED PZT PATCHES AND EMI-BASED METHOD

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EXTENDED ABSTRACT

Piezoelectric materials, such as lead zirconate titanate (PZT), can convert mechanical strain into an electric field and vice versa. This unique electro-mechanical transduction capability renders the material as sensors for structural health monitoring (SHM). The electro-mechanical impedance (EMI) technique using surface-bonded PZT (SBP) patches has become increasingly popular as a method for monitoring concrete material properties due to numerous advantages (Lim et al. 2021), such as ease of implementation (only one sensor is needed, see Fig. 1). Although this method has been proven effective in concrete monitoring (Soh and Bhalla 2005; Shin et al. 2008; Shin and Oh 2009; Su et al. 2019), there still exist some limitations in its applications. For example, statistical indexes, such as root mean square deviation (RMSD), are widely adopted to directly evaluate the changes of signals. However, they are associated with three main problems in concrete monitoring (a) The evaluation results are highly related to the initial baseline of RMSD; (b) The piezoelectric constants are sensitive to the temperature-induced changes (Ai et al. 2020), which would introduce large changes in RMSD values that can hardly be removed easily; (c) the deterioration of the adhesive layer and sensor itself would lead to signal changes and thus introduce errors to the evaluation results (Qing et al. 2006).

This paper presents experimental and numerical studies on the measurement of modulus of elasticity of standard concrete cubes (100*100*100 mm^3) using the PZT-based EMI technique. A new physical index (i.e., arctan(G/B)) is extracted from the obtained signals. The structural peaks, which show good repeatability performance and meanwhile are insensitive to the properties of sensors and adhesive layers, are selected (see Fig. 2(a)). The locations of the structural peaks could be accurately captured by finite element simulations, shown in Fig. 2(a). Based on the numerical model, the effects of the adhesive layer were also investigated. The results showed that the dimension of the adhesive layer and the temperature-induced changes in the properties of the adhesive layer would not lead to the horizontal movement of those structural peaks. The correlations between the movement trends of the selected structural peaks and the evolution of the modulus of elasticity during the curing age are established using numerical analyses. The regression results showed that there existed a linear relationship (see Fig. 2(b)) between the modulus of elasticity and the movement of the selected EMI peaks of concrete cubes. Furthermore, the figure shows the same results could be obtained by different sizes of PZT patches, including both small ($10\times10\times1.0$ mm^3) and big sizes ($20\times20\times1.0$ mm^3).

KEYWORDS

Piezoelectric materials, EMI, concrete monitoring, curing age, modulus of elasticity.

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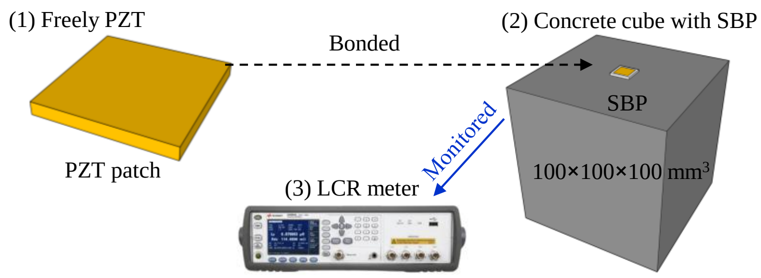
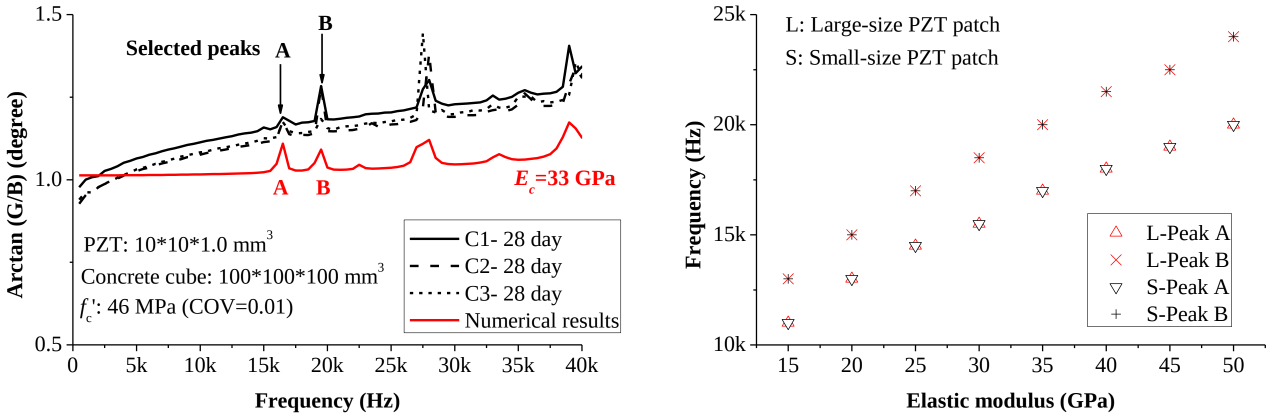


Figure 1. Set up for the elastic modulus measurement



(a) (b)

Figure 2. Experimental results and numerical results (a) Singal (b) E_c Vs. frequency

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LONG TERM BEHAVIOR OF EXTERNALLY PRESTRESSED GFRP-CONCRETE HYBRID BEAMS

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EXTENDED ABSTRACT

Externally prestressed GFRP-concrete hybrid beam (PC-FRP hybrid beam) is potential to be employed in bridge engineering, especially bridges in corrosive environments owing to several advantages, such as corrosion resistance, high strength, reduced short-term deflection, and convenient construction. The predictions of long-term behaviour of PC-FRP hybrid beam are so complicated due to the combined effects of concrete creep and shrinkage, creep of GFRP and relaxation of prestressing tendons, and the design calculation method has not been proposed. Besides, research findings on the long-term behaviour of EPGCHB are scarce (N. Deskovic et al. 1995; Mendes et al.2011; João R. Correia et al. 2013; Ibrahim Alachek et al. 2019; Xue et al. 2019). What's more, existing design guideline does not provide regulations for externally prestressed GFRP-concrete hybrid beams. Accordingly, the long-term behaviour should be investigated.

This paper presents an experimental program designed to examine the long-term behaviour of PC-FRP hybrid beam under sustained loading for 3000 days. The experimental program consisted of four PC-FRP hybrid beam and one non-prestressed GFRP-concrete hybrid beam (RC-FRP hybrid beam) (Fig. 1). The experiment variables included effective prestress (i.e., $0.35f_{ftk}$ or $0f_{ftk}$, where f_{ftk} is the tensile strength of CFRP tendon), shear connections (i.e., a single and double row of perforated FRP rib (PFR) or adhesive bonding), and load levels (i.e., 13.2 kN/m or 17.6 kN/m). Test results showed that (i) Mid-span deflection gradually increased with time. The long-term additional deflection increased rapidly after the first 1000 days of loading. The additional deflection of RC-1, PC-1, PC-2, PC-3 and PC-4 were 6.22 mm, 3.15 mm, 5.98 mm, 5.94mm and 6.10mm, which are approximately 80% compared to additional deflection at 3000 days. (ii) After 3000 days of loading, additional deflection of PC-FRP hybrid beam decreased by 46% compared to RC-FRP hybrid beam. And additional deflection of specimens with double rows of PFR decreased by 45% and 41% compared to specimens with a single row of PFR and adhesive bonding, respectively. Besides, additional deflection increased by 45% with loading increasing from 13.2kN/m to 17.6kN/m. (iii) The concrete and GFRP respectively satisfied the plane cross-section hypothesis, and the slips at the concrete slab-GFRP interface for PC-FRP hybrid beams and RC-FRP hybrid beam were within 0.05mm and 0.07mm respectively. (iv) After 3000 days of loading, the long-term-to-instantaneous strain of prestressed CFRP tendon increased by 10%.

Furthermore, a validated time-dependent finite-element model (FEM), considering the effect of the shrinkage and creep of concrete, the creep of GFRP, the relaxation of the tendon, and the interface slip, was generalized by FE software ABAQUS v6.14. The connection between GFRP and concrete slab was modelled by using the Cartesian elements and the value of its shear stiffness was adopted according to the results of shear load-slip curves. A detailed parametric study was then performed on 30 hybrid beams under sustained load for 50 years. It is found that additional deflection of hybrid beams after 7 years of loading is about 75-85% of additional deflection at 50 years.

A time-dependent theoretical analysis method, based on forces equilibrium and strain compatibility, is proposed to predict the long-term behaviour of EPGCHB. In this method, the effects of the creep and shrinkage of concrete, the creep of GFRP, relaxation of prestressing tendon as well as the interface slip between concrete and GFRP are considered. And the calculated results of the method are in good agreement with the test and FEA results.

KEYWORDS
GFRP-concrete hybrid beam; concrete creep and shrinkage; GFRP creep; externally prestressing; long-term behavior; finite element analysis; theoretical calculation method

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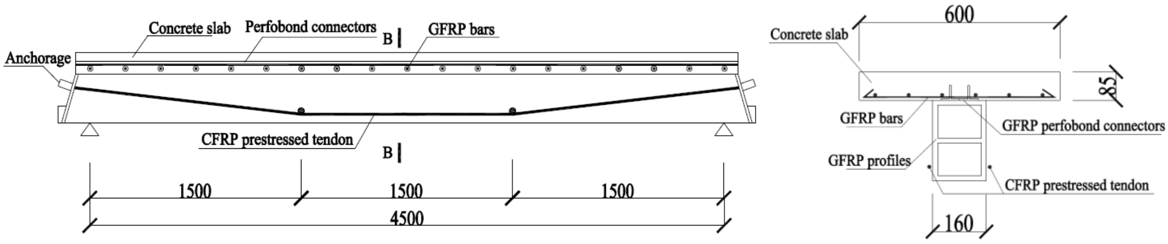

Figure 1. Cross-sections of externally prestressed GFRP-concrete hybrid beam

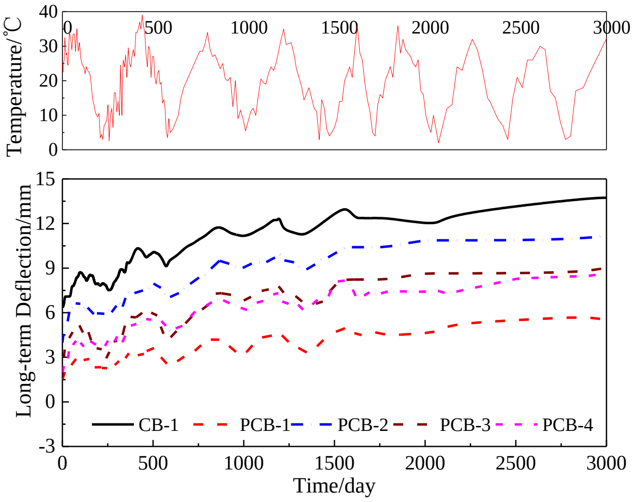

Figure 2. Typical time–deflection curves of beams with temperature

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DURABILITY OF BFRP REINFORCED SEAWATER SEA SAND CONCRETE STRUCTURE IN MARINE ENVIRONMENT

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EXTENDED ABSTRACT

Owing to the corrosion of steel bars, multiple durability issues arise in steel reinforced concrete structures under marine environment, leading to decreased serviceability of these structures and increased maintenance expenses (Wu et al. 2014). An effective approach of using fiber-reinforced polymer (FRP) bars instead of steel bars in marine infrastructure because of the good durability and lightweight of FRPs has been proposed to solve these problems (Wu et al. 2012). The durability of BFRP composites in different corrosion environments has been examined in previous studies (Wang et al. 2018; Wang et al. 2017), and it is revealed that the alkaline environment in normal and seawater sea sand concrete may adversely affect the long-term behavior of FRP. Since the failure of FRP initiates from the cracking of the matrix and the debonding of the interface between the matrix and fiber, improving the toughness and crack resistance of the matrix can prevent the invasion of corrosion solution, thereby enhancing the durability of FRP. Various approaches have been performed to toughen epoxy resin, including the addition of silica nanoparticles (Manjunatha et al. 2010), carbon nanotubes (CNTs) (Knoll et al. 2014) and rubbers (Shamsiah et al. 2016).

This paper focuses on the durability of basalt fiber reinforced polymer (BFRP) bar exposed to SSC environment, the durability tests of bonding behavior of BFRP bar and SWSSC beams were also conducted by acceleration of temperature. Modification of BFRP bars using CNTs was conducted, and the effect of modification on the durability of the bars was evaluated. The results showed that the modification using CNTs effectively slowed down the degradation rate of the tensile strength of the BFRP bar and the bond strength between the BFRP bar and SSC concrete in the marine environment (Fig. 1). Replacing ordinary BFRP stirrups with CNT-modified BFRP stirrups prevented the occurrence of shear-compression failure in the early stage of corrosion (Fig. 2). This indicates that the improved durability of the bond between the BFRP stirrups and the surrounding concrete after the modification has resulted in an improvement in the shear durability of the SWSSC beam. Additionally, the seismic behavior of concrete beams reinforced by steel bar and steel-FRP composite bar (SFCB) were investigated after 6 months of wet-dry cycles in seawater. The test results reveal that the SSC beam reinforced by SFCB and minibar exhibits high accumulative dissipated energy and less degradation after corrosion in the marine environment, which is 91.4% higher than that of the steel reinforced SSC beam (Fig. 3).

KEYWORDS

FRP bar, FRP stirrups, seawater sea sand concrete, CNTs, durability.

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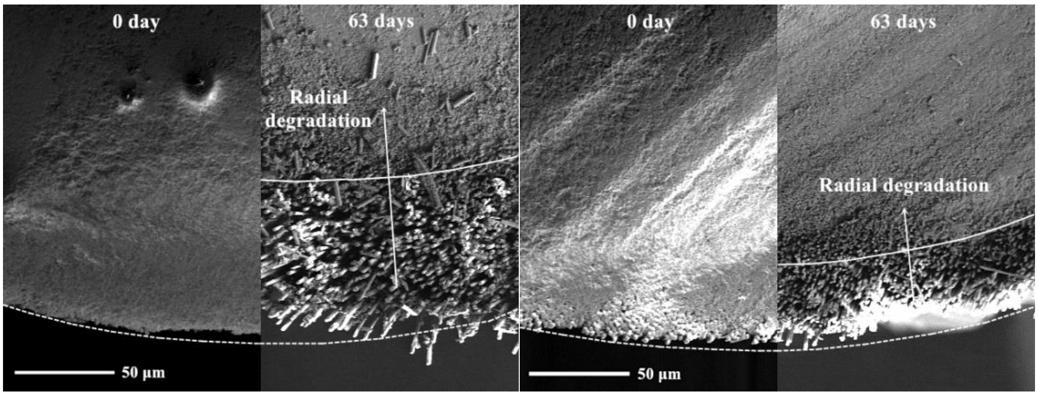

(a) BFRP bar (b) Modified BFRP bar

Fig. 1. SEM images for BFRP and modified BFRP bars exposed to SSC solution.

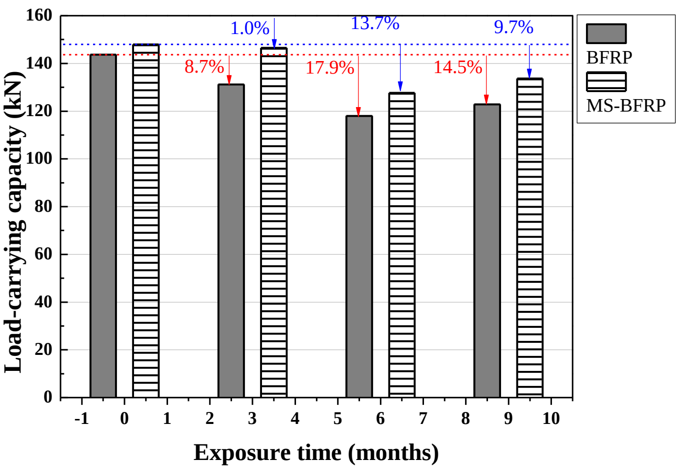

Figure 2. Effects of modified and adhering sand BFRP stirrups

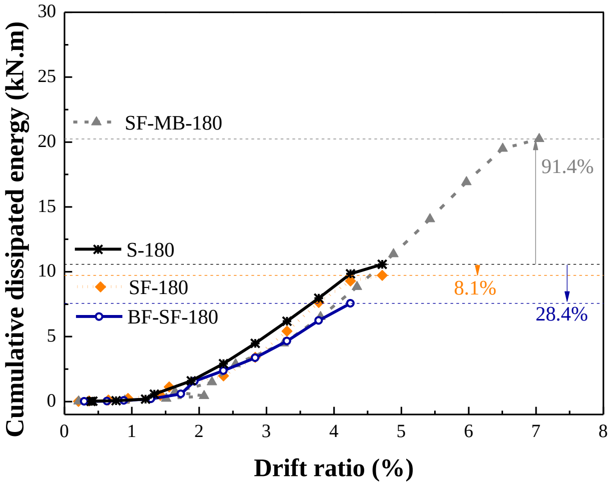

Figure 3. Cumulative dissipated energies of beam specimens after corrosion.

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EXPERIMENTAL INVESTIGATION ON AXIAL COMPRESSIVE BEHAVIOR OF FRP-ECC-HSC COMPOSITE STUB COLUMN

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EXTENDED ABSTRACT
Fiber Reinforced Polymer (FRP) confined concrete is widely used in engineering applications, including strengthening and repair of old structures and construction of new structures. With the effective confinement provided by FRP, concrete is under the state of triaxial stress and can exhibit significantly enhanced load capacity and ductility compared with unconfined concrete. High strength concrete (HSC) is showing the excellent advantages of increasing the structural bearing capacity, structural stiffness and reducing the self-weight. Similar to FRP-confined normal strength concrete (NSC), FRP-confined HSC can also achieve improved performance (Ozbakkaloglu and Vincent, 2014). However, due to the increased brittleness, HSC can develop localized shear creaks, which may cause highly concentrated hoop strain and FRP rupture in the same cracking locations. As reported in the literature, the average FRP rupture strain for FRP-confined HSC is lower than the corresponding FRP-confined NSC (Wu and Jiang, 2013). FRP-confining efficiency, which is determined by the ratio of average FRP rupture strain of the column over the FRP rupture strain obtained from material tests and generally in the range of 0.5-0.8 (Pessiki et al., 2001; Lam and Teng, 2004), would decrease with the increase of concrete strength (Lim and Ozbakkaloglu, 2014). This indicates that a relatively poorer confinement may be provided for FRP-confined HSC. For the ultimate conditions, the enhancement ratios of both compressive strength and axial strain are reduced for FRP-confined HSC as well (De Oliveira et al., 2019). Therefore, the weakened structural performance, especially ductility behavior, causes a big obstacle to the engineering application of FRP-confined HSC columns.

In this study, a novel FRP-ECC-HSC composite column is proposed to improve the compressive behavior of FRP-confined HSC columns. The sectional arrangement is shown in Figure 1. It has an FRP tube, an engineered cementitious composite (ECC) ring and a high strength concrete (HSC) core. With the excellent tensile and cracking behavior, ECC ring is used to redistribute the hoop stress and strain from HSC core to FRP tube in the proposed composite column. It will lead to a much more uniform hoop strain distribution on the FRP tube. Therefore, the FRP premature rupture will be mitigated with an improved FRP confining efficiency. The fully utilization of FRP confining material will also delay the column failure. Both compressive strength and deformation ability will be further enhanced accordingly. A total of 12 stub columns with different HSC core strengths (i.e., 75 MPa or 97 MPa) and ECC ring thicknesses (i.e., 15 mm or 25 mm) were tested under axial compression. Typical axial load-strain curves are presented in Figure 2. It is found that FRP-ECC-HSC composite columns can develop larger FRP confining efficiency with more uniform hoop strain distribution in comparison to the corresponding normal FRP-confined HSC columns. The ultimate axial strain is obviously enhanced as well for this newly developed composite column, leading to an improved ductile compressive behavior.

KEYWORDS
FRP-ECC-HSC, composite column, hoop strain, confining efficiency, ductility.

ACKNOWLEDGEMENT
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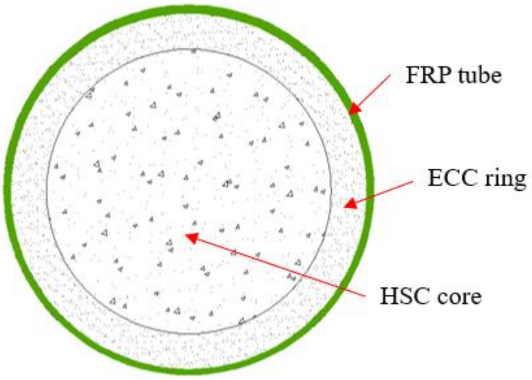

Figure 1. Cross-section of FRP-ECC-HSC composite column

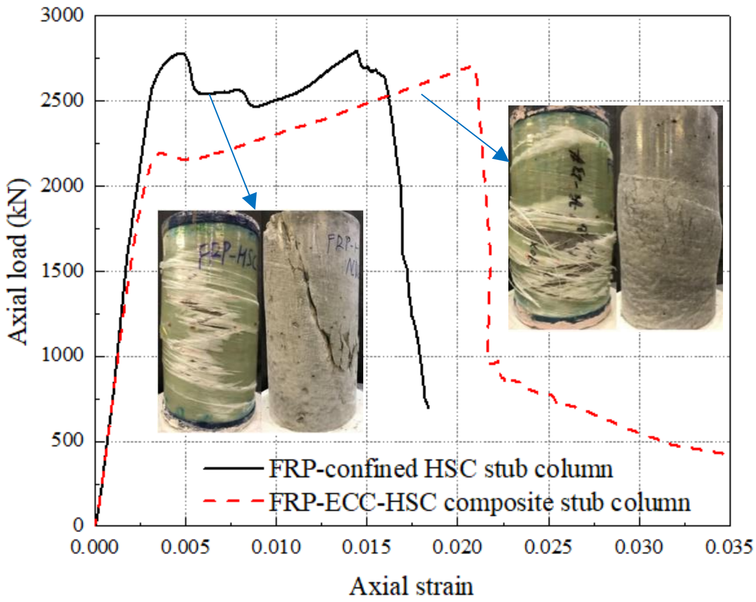

Figure 2. Typical axial load-strain curves

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DUCTILE ULTRA-HIGH STRENGTH REINFORCED CEMENTITIOUS COMPOSITES BASED ON MULTISCALE FIBROUS REINFORCEMENTS: MODELING AND IMPLEMENTATION

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EXTENDED ABSTRACT

Due to the corrosion of the chloride ions, the seawater sea-sand concrete (SSC) is not compatible with the steel rebar reinforced concrete. The fibre reinforced polymer (FRP) are becoming an attractive substitute for the steel because of the excellent corrosion resistance and the mechanical performance. FRP reinforced SSC have a wide application prospect in the prefabricated member for the column jacket, permanent formwork, exterior protection of the existing structure and thin-shell structure in ocean engineering (Ahmed et al. 2020; Benzecry et al. 2021; Dong et al. 2019). Currently, many combination of FRP and short fibre reinforced cementitious composites, such as, Engineering Cementitious Composite (ECC) and Ultra High Performance Concrete (UHPC), are becoming increasingly popular due to the high tensile performance, energy absorption capacity and crack-width control capability (Barhum and Mechtcherine 2013; Deng et al. 2020; Li et al. 2019; Meng et al. 2018). In essence, the fibrous material applied to reinforce the cementitious matrix has a wide range of scales, ranging from the distributed short fibres with nanometre and milli-metre length to aligned continuous fibrous reinforcements. With respect to the bond-slip mechanism and the fiber bridging theory, the tensile performances of the composite containing the fibre in a single scale would vary greatly, as shown in Fig. 1. Nevertheless, when the cementitious matrix was toughened by reinforcing fibres in multiple scales and different types jointly, the unique mechanical tensile behaviour could be observed through an amount of existing experiments. Such behaviour for fibres reinforced cementitious composite is attributed to the combined actions between the fibres in different scales and the brittle matrix, which is related to the volume fraction, the physical properties and the nonuniform distributions of reinforcing fibres and matrix.

To investigate these issues, the concept of multi-scale fibres reinforced cementitious composite (MSFRC) is presented. The combined actions for MSFRC, such as tension stiffening, ductility enhancing and synergetic effects, are defined and explained theoretically. In addition, to simulate these combined actions and tensile behaviour for MSFRC, a discrete element model is developed on the basis of the spring elements, crack band theory and Monte Carlo simulation. The matrix property, fibre scales and types, randomness of imperfections have been considered in the model. Finally, the data of six independent tensile experiments (steel reinforced concrete, PVA-ECC, PE-ECC, UHPC, UHPC-rebar, ECC-FRP) obtained from literatures were simulated and presented (Kim 2009; Hung et al. 2019; Li et al. 2001; Yu et al. 2020; Zheng et al. 2018). It is found that the predicted mechanical response and crack evolution process match well with the experimental results. Accordingly, the typical failure modes and the mechanism of MSFRC can be explained through the presented model. Furthermore, the ductile ultra-high strength reinforced cementitious composites were designed, attaining compressive Strength exceeding 130MPa, equivalent flexural Strength of over 50MPa and ultimate tensile strain of over 1.3%.

KEYWORDS

Multi-scale fibrous reinforcement; cementitious composites; tension stiffening; discrete element model (DEM); Monte Carlo simulation.

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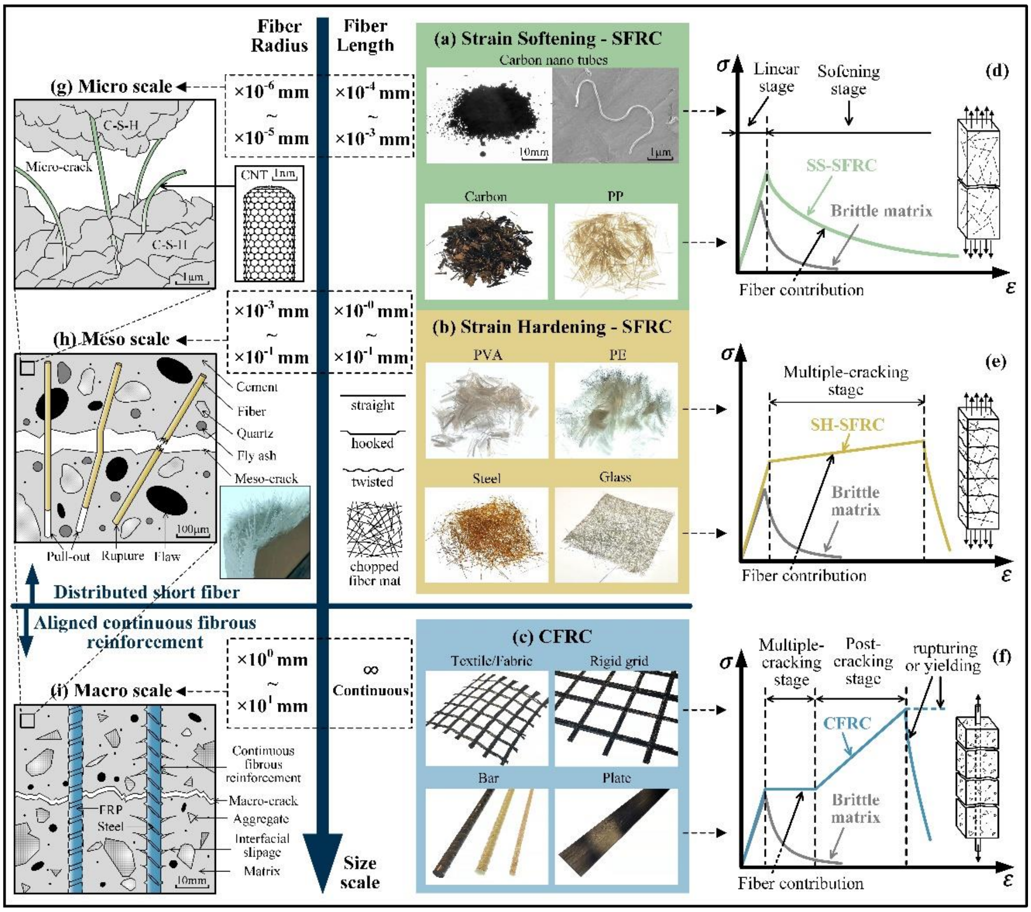

Figure 1. Schematic of multiscale reinforcing fibers and the tensile performance of the composites: (a)-(c) the fiber material types and geometry properties for Strain Softening (SS)-Short Fiber Reinforced Cementitious composites (SFRC) , Strain Hardening (SH)-SFRC and Continuous Fiber Reinforced Cementitious composites (CFRC), including the carbon nanotube at the micro-scale level (the SEM image from Ref. (Xu et al., 2015)), short fibers at the meso-scale level and continuous fibrous reinforcement at the macro-scale level, (d)-(f) the cracking patterns and typical tensile behavior of the SS-SFRC, SH-SFRC and CFRC, (g)-(i) the bridging representation of reinforcing fibers at the individual scale levels.

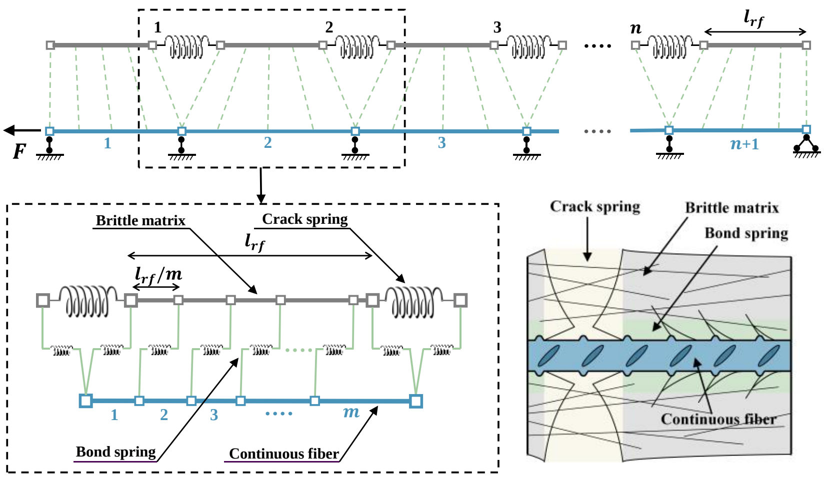

Figure 2. The proposed discrete model.

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SHEAR AND IMPACT PERFORMANCE OF BFRP BARS AFTER EXPOSURE TO THE SEAWATER SEA-SAND CONCRETE ENVIRONMENT

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EXTENDED ABSTRACT
Numerous investigations have been carried out on replacing steel bars with fiber-reinforced polymer (FRP) bars to reinforce marine construction and sea-water sea sand concrete in recent years. However, the strong alkaline environment inside the concrete can adversely affect the durability performance of FRP materials despite its superior resistance to chloride corrosion. The rich hydroxyl ions can depolymerize the ester bonds of resin and corrode the internal glass or basalt fibers (Kamal et al. 2011). The deterioration can increase the porosity of the FRP composite (Won et al. 2008.) and allows the penetration of water, alkali, and other detrimental ions, resulting in the deterioration of the whole FRP composite. Due to the aggressivity of hydroxyl ions to resin and internal fibers, the GFRP, BFRP, and CFRP bars exposed to the alkaline solution for 180 days also exhibit significantly lower tensile strength than those exposed to seawater and tap water (Lu et al. 2020). It has also been reported that the alkalinity is crucial for BFRP bar degradation (Lu et al. 2020). BFRP bars subjected to an alkaline environment show weakened mechanical strength, microstructure degradation and evidence of alkali-silica reaction between the BFRP bar and cement matrix. Currently, the use of BFRP bars in SWSSC has been limited due to their instability in alkaline environments.

This paper evaluates the effect of reduced alkalinity on mitigating the deterioration of BFRP bars in seawater sea sand concrete (SWSSC) environment. The shear performances of BFRP bars in different simulated SWSSC pore solutions (pH=13.2, 12.3 and 10.1) and in SWSSC with different alkalinities were studied using accelerated degradation tests. Portland cement is partially replaced by silica fume to reduce the pH value of seawater sea sand mortar. The experimental results indicate that BFRP bars in low-alkalinity simulated pore solutions and SWSSCs suffered less transverse or interlaminar shear strength loss (Figs. 1 and 2). The low-velocity impact performance of BFRP bars is also examined after exposure to the SWSSC environment for 24, 48, and 72 days and elevated temperatures (25, 40, and 55°C). The maximum load-bearing capacity, deformation capacity, and energy absorption capacity of the deteriorated BFRP bars are measured. It was revealed that both the fracture threshold and the bending stiffness of BFRP bars generally decrease with the elevated exposure temperature and duration. The degradation of BFRP bars includes resin hydrolysis, fiber-resin interface debonding and basalt fiber corrosion (Fig. 3). This study provides some insights to promote the application of BFRP bars in the SWSSC.

KEYWORDS
BFRP bar, seawater sea-sand concrete, low-alkalinity, shear performance, impact performance.

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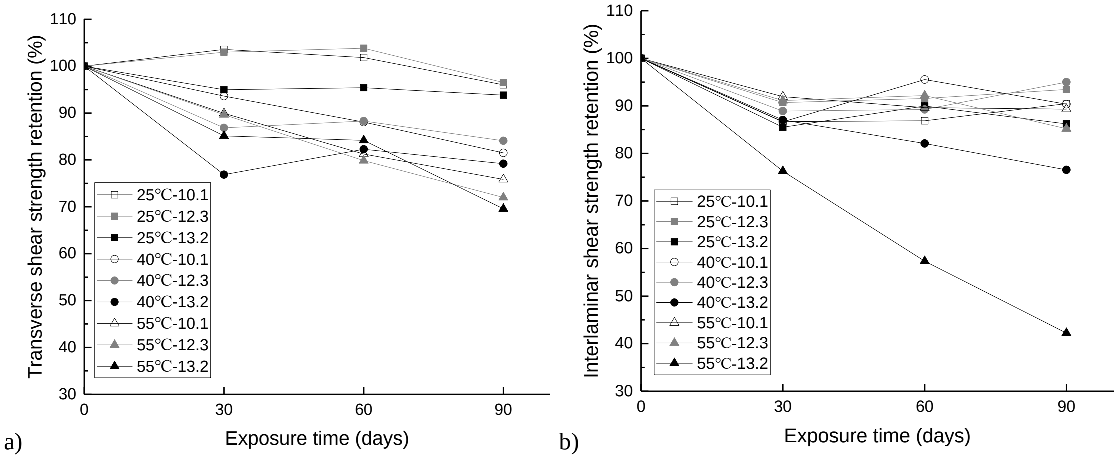

Figure 1. Shear strength evolution of BFRP bars exposed to simulated SWSSC pore solutions with different alkalinities, (a) transverse shear strength, (b) interlaminar shear strength

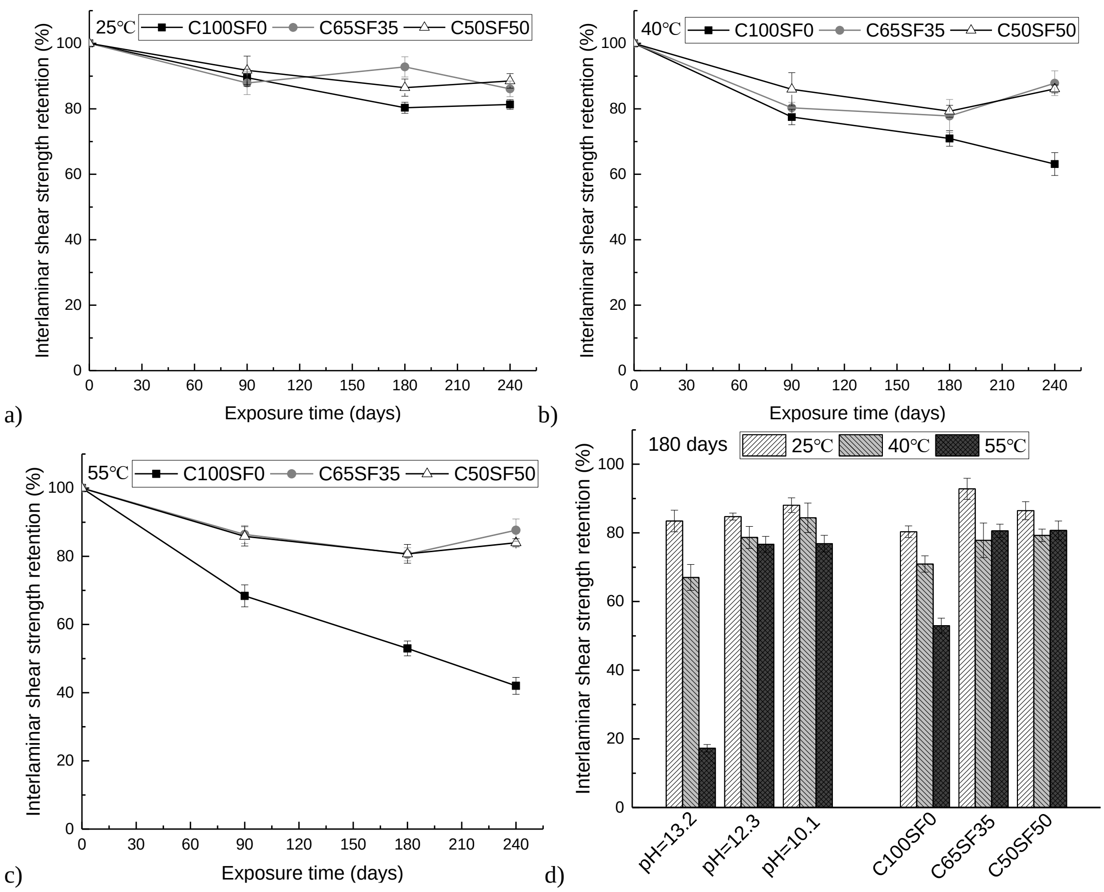

Figure 2. Interlaminar shear strength retentions of BFRP bars embedded in SWSSMs with different alkalinities at the temperatures: (a) 25℃, (b) 40℃, (c) 55℃, (d) a comparison of bare and embedded BFRP bars after 180 days exposure

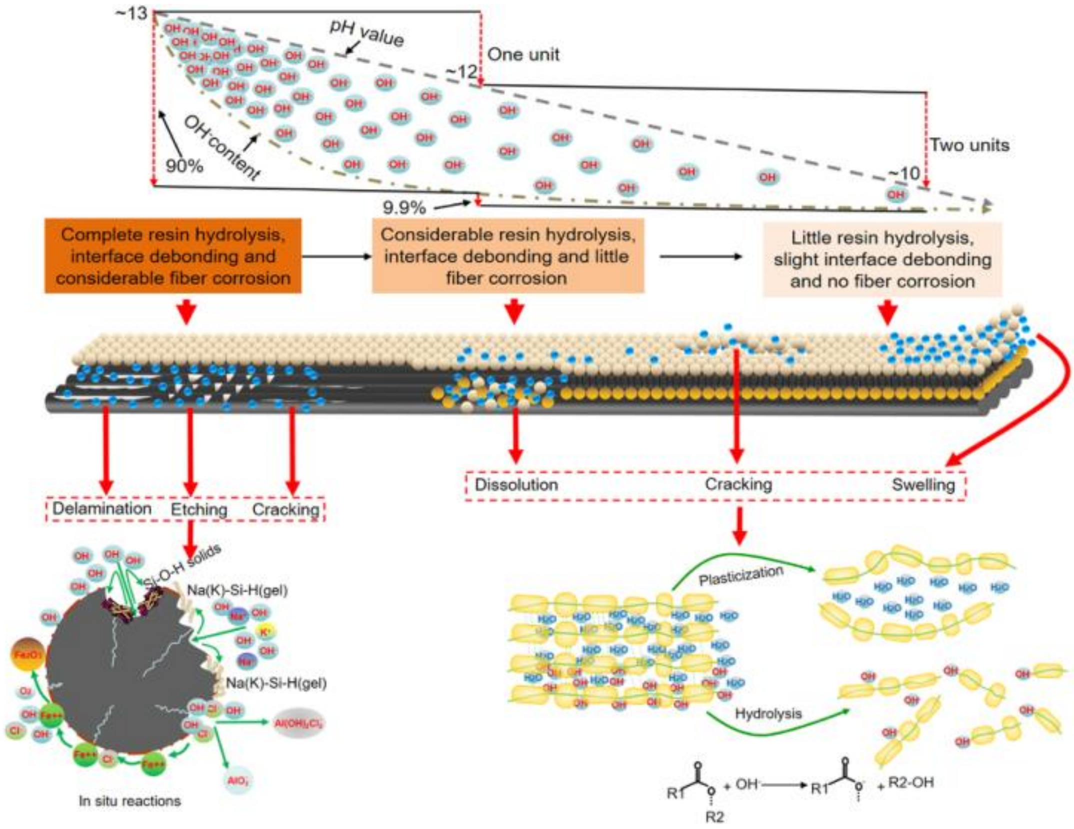

Figure 3. Degradation mechanisms of BFRP bar in SWSSC environment

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LIFE-CYCLE COST AND ENVIRONMENTAL IMPACT ASSESSMENT OF COMPOSITE STRUCTURES

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EXTENDED ABSTRACT
Concrete and steel production are seen as major contributors to global anthropogenic greenhouse gas (GHG) emissions (Miller et al. 2016; Quader et al. 2014). The high rehabilitation cost of corroded reinforced concrete has become an issue to be addressed (Bastidas-Arteaga and Stewart 2016). Composite structures are considered an effective solution to the abovementioned problems. Fiber-reinforced polymer (FRP)-concrete structures, among others, are gaining much attention in recent years, especially for their great corrosion-resistance. However, limited efforts have been devoted to investigating the composite structures from a life-cycle perspective, i.e., environmental impact and cost-effectiveness. A nonmonetary evaluation model was developed to identify the life-cycle benefit-cost of concrete-filled steel tubular columns and FRP-confined concrete structures (Hastak and Halpin 2000), which was further refined to an advanced framework that utilizes material properties to assess the performance-based life-cycle cost of composite materials in construction (Hastak et al. 2016). Other studies were carried out to compute life-cycle cost or environmental impacts of FRP reinforced concrete, FRP components or structures (Cadenazzi et al. 2020; Eamon et al. 2012; Li et al. 2013; Maxineasa et al. 2015; Nishizaki et al. 2006; Smith 2015). Nevertheless, most of the previous research are presented in a deterministic manner without considering uncertainties embedded in the assessment process (Groen et al. 2017). Uncertainty plays a significant role within the life-cycle assessment process and the effect of various uncertainty on the life-cycle performance could be very different (Frangopol et al. 2017; Guo et al. 2020). Arbitrariness may be induced in weighing design options if not considering uncertainties.

Against the above background, this paper investigates the environmental impact and cost-benefit of FRP-concrete structures via life-cycle analysis (LCA) and life-cycle cost analysis (LCCA) (ISO 2006; Russell-Smith and Lepech 2009). The quantitative analysis is presented by computing the life-cycle environmental impact and life-cycle cost of comparative cases including but not limited to concrete-filled fiber-reinforced polymer (FRP) tubular column (CFFT); and hybrid FRP-concrete-steel double-skin tubular column (DSTC) (Fig. 1). The developed approach could also be applied to other structural components and systems. The DSTC is designed to reduce concrete consumption by leaving a void at the center of the column (Teng et al. 2007), while the outer FRP tube is expected to pretend the inner steel tube from corrosion. Both deterministic and probabilistic results are discussed in this research. The deterministic LCA results indicate that CFFT has the least CO_2 emission: 50 % less than DSTC. While LCCA results show that for the investigated scenario the DSTC costs the most across the studied service life, about 15 % more than CFFT. The probabilistic results indicated that the DSTC generally has more environmental impact than CFFT while its costs can be possibly lower than CFFT (Fig.2).

KEYWORDS
Fiber-reinforced polymer (FRP), concrete, CO_2 emissions, life-cycle cost analysis, uncertainty analysis.

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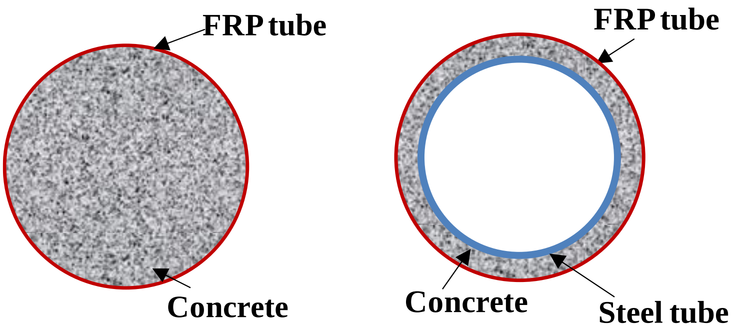

a. CFFT b. DSTC

Fig. 1. Cross-section profile of the studied cases

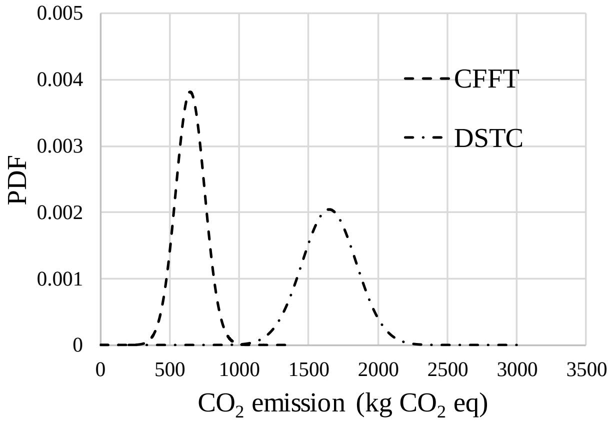

Fig. 2a. Probability Distribution Function (PDF) of life-cycle CO_2 emission

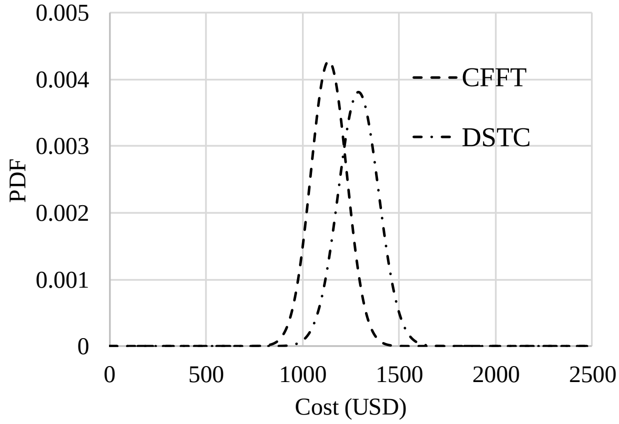

Fig. 2b. Probability Distribution Function (PDF) of life-cycle cost

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SHEAR BEHAVIOUR OF SWSS-SCC STRUCTURES REINFORCED WITH GFRP LONGITUDINAL BARS AND GFRP STIRRUPS

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EXTENDED ABSTRACT

It has become increasing evident that deterioration of ageing concrete infrastructures and a drive for low-energy, yet highly durable concrete structures has been one of major challenges facing designers, inspectors, assessors and owners (Wahid Ferdous *et al.* 2015). It has been well reported that Glass Fibre Reinforced Polymer (GFRP) and Self-Compacting Concrete (SCC) with high volume industrial wastes are two emerging construction materials that can be widely adopted to replace steel reinforcing bars and traditional cement-based concrete, respectively (Taylor et al.2016; Zheng et al. 2019). Also, to effectively utilize the corrosion-free properties of FRP reinforcement, seawater and sea sand materials were adopted in the mixing of concrete to produce seawater and sea sand self-compacting concrete (SWSS-SCC). Those novel construction materials are expected to address deterioration problems induced by steel corrosions and to deal with the sustainable issue due to the production of cement. However, few studies deal with the combined use of these sustainable materials and this has been the key motivation of this undertaking. The shear behaviour of FRP reinforced SWSS-SCC concrete beams is still little understood (. To gain wide acceptance in construction market, the shear behaviour of SWSS-SCC beams reinforced GFRP bars should be investigated.

This paper presents an experimental investigation of SWSS-SCC concrete beams reinforced longitudinally with GFRP bars and transversely with GFRP stirrups (Fig.1). In this test, nine full-scale beams were conducted and tested under four-point loading up to failure. The major investigated experimental variables were the shear span to depth ratio (a/d), the longitudinal reinforcement percentage, existing FRP stirrup and the height of concrete beams. It is evident in test results that the shear capacity of test specimens was enhanced by using GFRP stirrups, increasing longitudinal FRP reinforcement ratio and reducing the span-to-depth ratios. In addition, size effect still exists in the test specimens the test specimens with GFRP stirrups. Interestingly, the GFRP stirrups were effective in suppressing the size effect on shear strength of FRP reinforced concrete beams. However, the size effect on shear failure could not be eliminated completely, such as shear cracking width, contribution components of shear resisting mechanism and normalized shear strength. Comparing the test results with the predicted results from the theoretical models reported in the literatures (ACI 2015, CSA S806 2012), the CSA S806-12 has shown the most accurate predictions. Thereafter, a reliable database consisting of 120 test specimens obtained from literature is collected, and an artificial neural network (ANN) model has been developed to predict the shear capacity of concrete beams reinforced with FRP bars and stirrups. The prediction results of the ANN model are compared with the theoretical models, and the accuracy and validity of the proposed ANN model are verified.

KEYWORDS

GFRP bar, GFRP stirrup, self-compacting concrete, shear behaviour, size effect.

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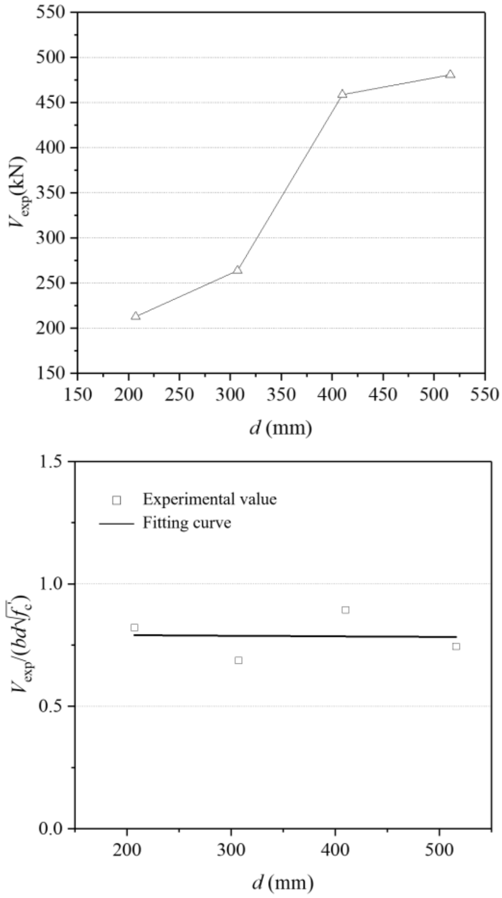
(a) GFRP Bars (b) GFRP Stirrups

Figure 1. Longitudinal GFRP reinforcing bar and GFRP stirrup adopted in this test



(a) shear capacity versus effective depth (b) nominal shear strength versus effective depth

Figure 2. Size effect on shear capacity of beams reinforced with GFRP bars and GFRP stirrups

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STAINLESS STEEL CORROSION BEHAVIOUR IN CHLORIDE-CONTAMINATED CONCRETE UNDER MARINE EXPOSURE

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EXTENDED ABSTRACT

To promote the circular economy in the construction sector, natural resources, e.g. fresh water and virgin rocks, used in the concrete production can be replaced by chloride-contaminated raw materials. However, the real suitability of this solution to produce reinforced concrete structures can be assessed only through a deep evaluation on the concrete long-term behavior in different exposure environments, that allows determining the possible benefits in terms of improved sustainability. The majority of the available studies showed the unsuitability of seawater, recycled aggregates contaminated by chlorides and sea sand in the concrete production together with carbon steel reinforcement due to its high vulnerability to corrosion (Mohammed et al. 2004; Debieb et al. 2010; Dias et al. 2008). On the other hand, few studies are available on the performances of non-conventional reinforcement, as stainless steel, GFRP or epoxy-coated bars in chloride-contaminated concrete (Ebead et al. 2022). In the framework of the SeaCon project "Sustainable concrete using seawater, salt-contaminated aggregates, and non-corrosive reinforcement", financed by the Infravation program, the use of stainless steel reinforcement in combination with chloride-contaminated concrete was studied to construct durable and sustainable concrete infrastructures.

This paper presents the corrosion behavior of two austenitic (304L and XM-28) and two duplex (23-04 and 22-05) stainless steels when embedded in alkaline and carbonated concrete, made with chloride-contaminated raw materials and exposed to the further chloride penetration. Concretes were made with a water/cement ratio of 0.52 by replacing virgin raw materials, i.e. cement, water and aggregate, respectively with a chlorides-contaminated cement (with or without addition of carbon fly ash: CEM or CEM-FA), seawater (Sea) and chloride-contaminated recycled aggregate (RCA). For comparison a reference concrete (Ref) without chloride-contaminated raw materials was considered. Alkaline reinforced specimens were exposed to the ponding with a 3.5% NaCl solution for approximately two years, followed by wet and dry cycles with the same solution. Carbonated reinforced specimens were exposed to the further chlorides penetration with a 3.5% NaCl solution for approximately 1 year. The exposure to ponding did not lead to the onset of corrosion on any of the stainless steel bars embedded in alkaline concrete made with chloride-contaminated materials, even when a chloride content of about 4% by mass of cement was reached at the bar depth, whilst corrosion occurred on XM-28 bars embedded in alkaline Sea and RCA concretes during the wet and dry cycles (Fig. 1). The use of chloride-contaminated raw materials for the production of concrete seems to be allowed in combination with 304L, 23-04 and 22-05 also when carbonation reaches the bar depths and concrete was exposed to the further chloride penetration (Fig. 2). Conversely, XM-28 showed the initiation of corrosion when exposed to chloride exposure.

KEYWORDS

stainless steel bar, chloride-contaminated concrete, carbonation, chlorides, corrosion behaviour, natural exposure, circular economy.

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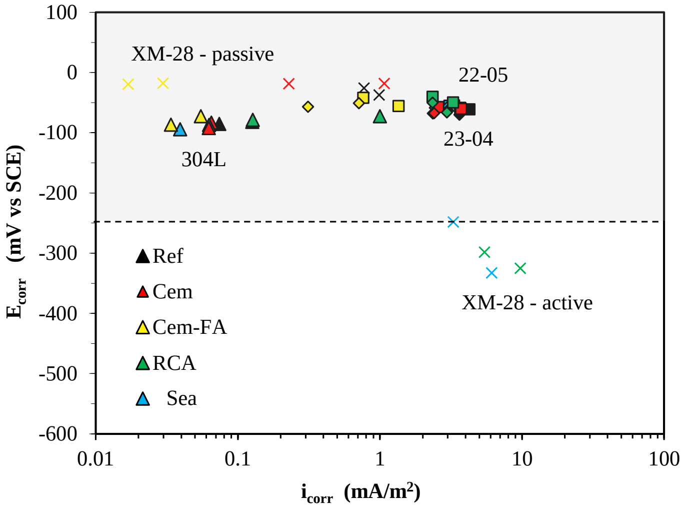

Figure 1. Relationship between the average values of corrosion current density, i_{corr}, and corrosion potential, E_{corr} measured during the wet and dry cycles with a 3.5% NaCl solution on different types of bar embedded in alkaline concrete made with different chloride-contaminated raw materials (grey area represents negligible corrosion conditions)

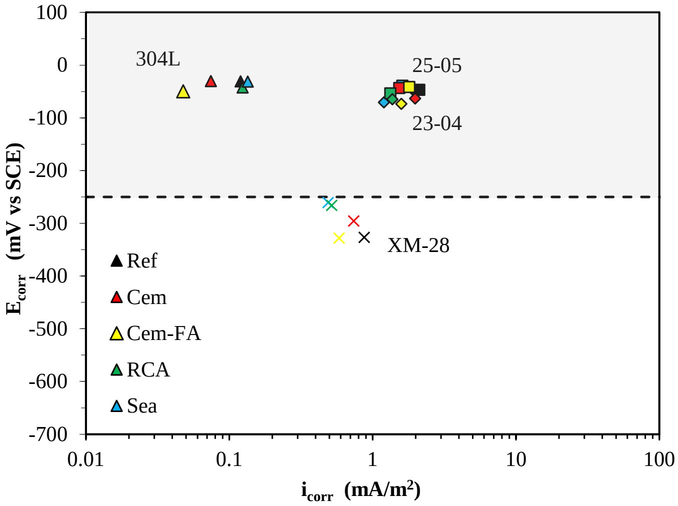

Figure 2. Relationship between the average values of corrosion current density, i_{corr}, and corrosion potential, E_{corr}, measured during the ponding exposure on different types of bar embedded in carbonated concrete made with different chloride-contaminated raw materials (grey area represents negligible corrosion conditions)

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SIMULATION OF MULTI-SPECIES KINETICS IN CONCRETE AND ITS POSSIBLE APPLICATION TO SEA-WATER SEA-SAND CONCRETE

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EXTENDED ABSTRACT

Reinforced concrete structures suffer the deterioration risk by steel corrosion, which is an electro-chemical process relating to the electric field and chemical components of metal and electrolyte. As the electron-carrying medium, the multi-species in concrete serving as electrolyte play an important role. Therefore, it's keen to know the dynamic equilibrium of these species in pore solution and matrix of concrete under the spatial circuit and macro-cell corrosion. With the integrated simulation platform, the multi-species kinetic in concrete is evaluated including calcium, hydroxide, etc. (Wang et al. 2021). Especially for calcium ion, it's found that its initial concentration and supply of carbon dioxide have significant impact on the ion distribution profile of Ca^{2+}, see Fig. 1. Accordingly, three mechanisms are summarized based on the simulation result as well as the experiment.

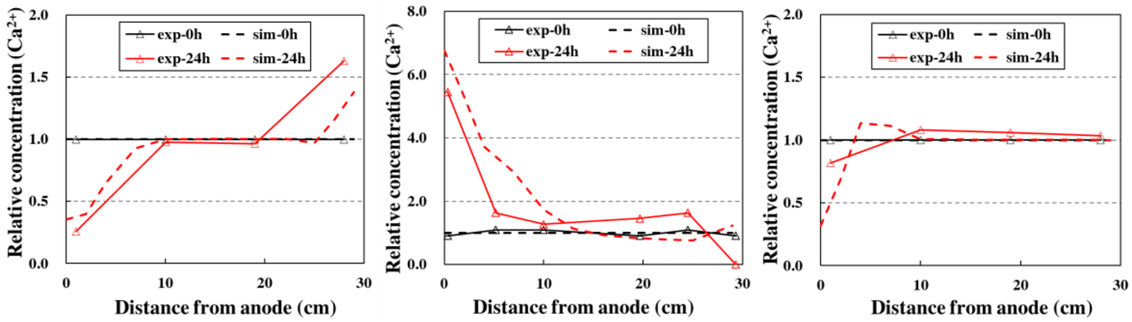

Figure 1. (a) less $Ca(OH)_2$, less CO_2 (b) less $Ca(OH)_2$, much CO_2 (c) much $Ca(OH)_2$, less CO_2

In fact, the function to handle multi-species kinetics is also integrated in the platform to achieve the hydration of cementitious material and the evolution of micro-pore structures (Maekawa et al. 2003; Elakneswaran and Ishida 2014). Thus, to apply the numerical analysis with the concrete exposure to coastal environment as well as sea-water sea-sand concrete becomes possible through this platform. One simple example is presented, where a cubic concrete specimen made of Ordinary Portland Cement is cured in pure water for 28 days and then exposed to the aggressive ions such as sulphate and bicarbonate. The continuous volume change of several hydrates is recorded, which is calculated based on the dynamic multi-species equilibrium, see Fig. 2. It is found the detrimental ions has different impacts on the change of chemical components of matrix, which may cause degradation. Another example shows the curing of sea-water sea-sand concrete where halite crystal is mixed with pure water to simply represent the impact from sea-water and sea-sand. The volume change of hydrates is plotted together with the micro-pore structure formation and strength evolution, see Fig. 3. It yields that the chloride can trigger the formation of ettringite and Friedel's salt and thus lead to smaller porosity and larger strength.

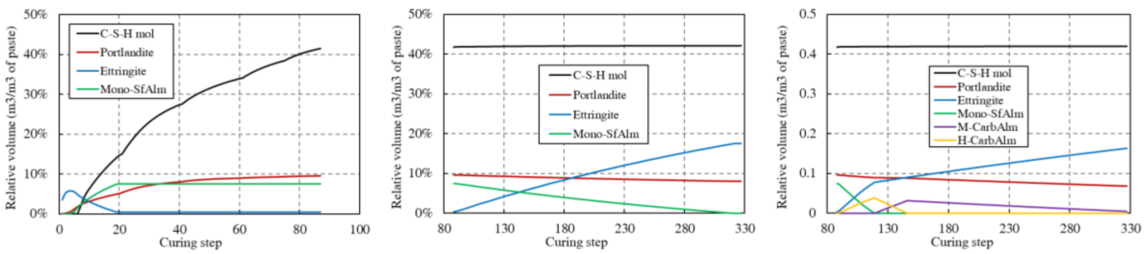

Figure 2. Hydrates volume change of OPC concrete (a) curing (b) SO_4^{2-} attack (c) SO_4^{2-}+HCO_3^- attack

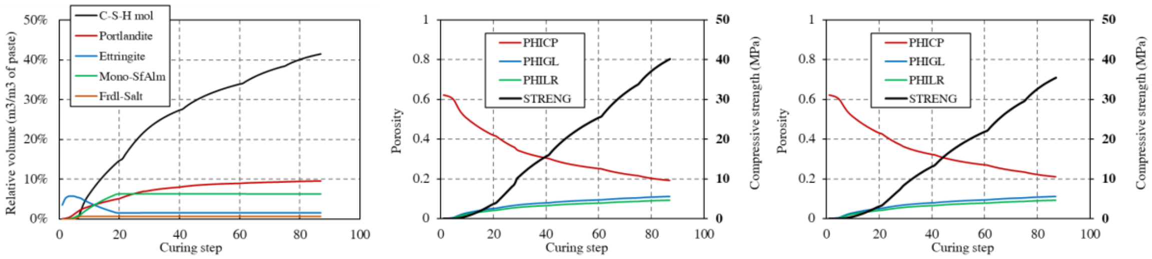

Figure 3. (a) hydrates volume change of SSC (b) micro- porosity&strength of SSC (c) micro-porosity&strength of OPC concrete

Furthermore, the platform also includes the macroscale mechanical calculation of structural members, which is coupled with the microscale material science through mesoscale cracks (Wang and Maekawa 2021), see Fig. 3. Therefore, the multi-scale and life-span evaluation of the marine infrastructures made of OPC concrete and sea-water sea-sand concrete is another possible application in the future.

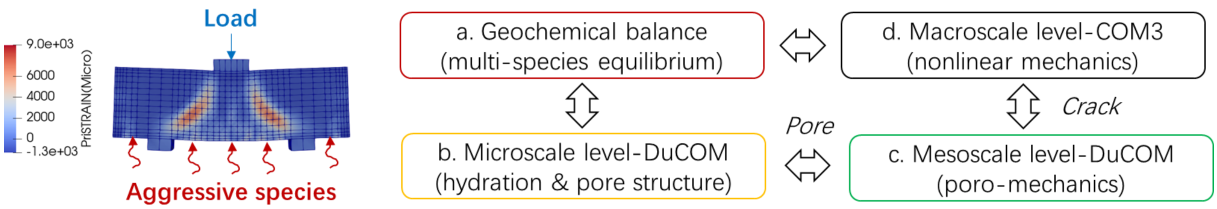

Figure 3. Multi-scale and life-span evalution with integrated simulation platform

KEYWORDS
Multi-ion kinetics, numerical simulation, reinforced concrete, coastal environment.

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EXPERIMENTAL AND NUMERICAL RESEARCH ON THE DIFFUSION-DEGRADATION PROCESS OF GFRP COMPOSITE

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EXTENDED ABSTRACT
Glass fiber-reinforced polymer (GFRP) composite has been considered as a good alternative to conventional steel reinforcements in concrete structures for avoiding salt-induced steel corrosion. However, the tensile strength of GFRP composite may gradually decrease when it is exposed to harsh environments (Wang et al., 2017). This phenomenon can be explained by the fact that the water molecules and alkaline ions from the concrete pore solution may penetrate the vinyl ester (VE) matrix and then chemically react with glass fibers, resulting in the tensile degradation of the whole GFRP composite. Even though previous studies have conducted numerous laboratory-scale tests (Benmokrane et al., 2017) and in-situ field tests (Benmokrane et al., 2018) on GFRP degradation, a systematic study on the water/ion diffusion and fiber degradation process of GFRP composite versus aging time is yet to be conducted.

In this paper, a water diffusion-degradation framework of GFRP composite involving water diffusion coefficient of VE matrix and degradation rate of glass fibers is proposed. Firstly, the water diffusion coefficients of VE matrix and GFRP composite are experimentally obtained according to Fick's law. Fig. 1 illustrates that the diffusion coefficient of GFRP composite ($D_{effective}$) over the diffusion coefficient of VE matrix (D_{matrix}) presents an almost linear downward trend against the fiber volume fraction (V_f) of the GFRP composite. Assuming the chemical reaction to have a negligible effect on the diffusion process, composite diffusivity obtained from finite element analysis is found to be in good agreement with test data. Then the tensile degradation of single VE-coated glass fiber against aging time is tested at different temperatures (23 ºC, 40ºC and 60ºC). Finally, taking a GFRP rebar ($V_f = 82.3\%$) as an example, short-term accelerated water immersion test is carried out at 60 ºC for up to 12 months. After the water concentration versus time at different parts of the GFRP rebar is determined from diffusion analysis, the local fiber degradation can be obtained and integrated to find the strength reduction of the rebar. As shown in Fig. 2, both the water uptake and tensile strength degradation of numerical results are consistent with that of the experimental data, validating the correctness of the proposed water diffusion-degradation framework. This framework can be further used to predict the durability performance of GFRP composites with varying geometry and V_f.

In comparison to water, the alkaline solution with higher pH levels may lead to severer degradation of GFRP composites (Chen et al., 2006). Based on test results under different pH levels (pH=11, 12 and 13), D_{matrix} is found to be insensitive to the alkalinity but the a significant amount of hydroxide ions may be consumed by the nearby glass fibers. Given this, the chemical reaction between glass fibers and hydroxide ions is introduced in the revised diffusion-degradation framework. Some preliminary results will be introduced in the last part of this talk.

KEYWORDS
GFRP composite, glass fiber, vinyl ester matrix, diffusion coefficient, tensile degradation.

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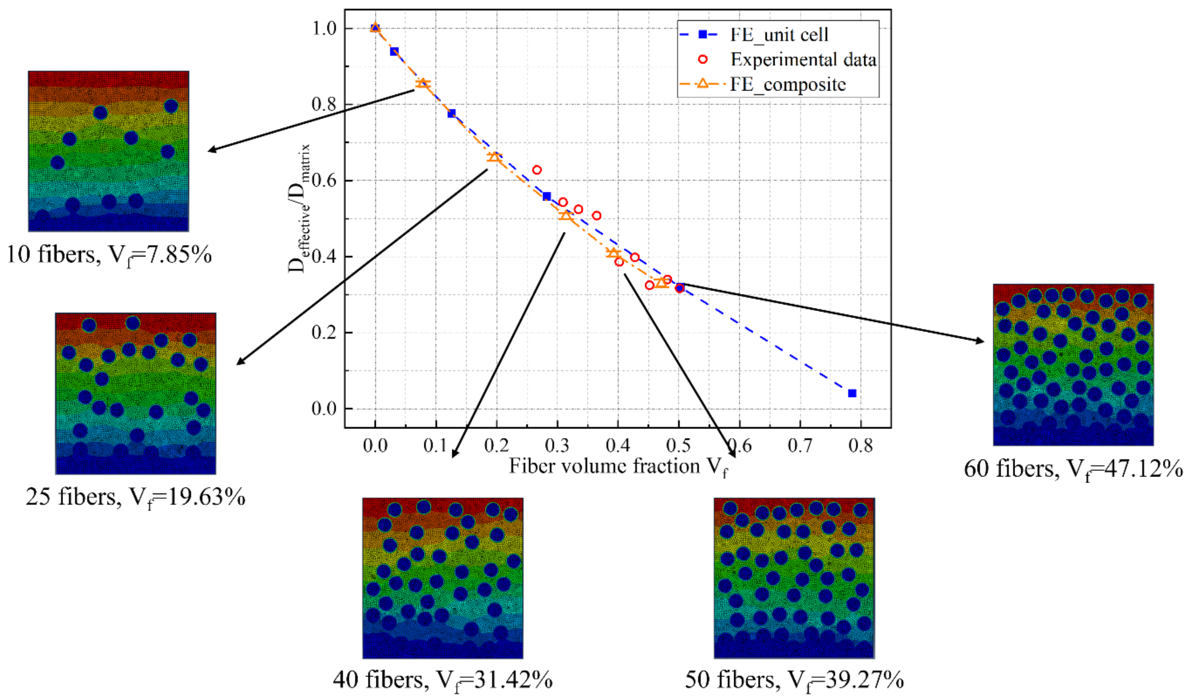

Figure 1. The relationship between GFRP composite's diffusion coefficient and fiber volume fraction.

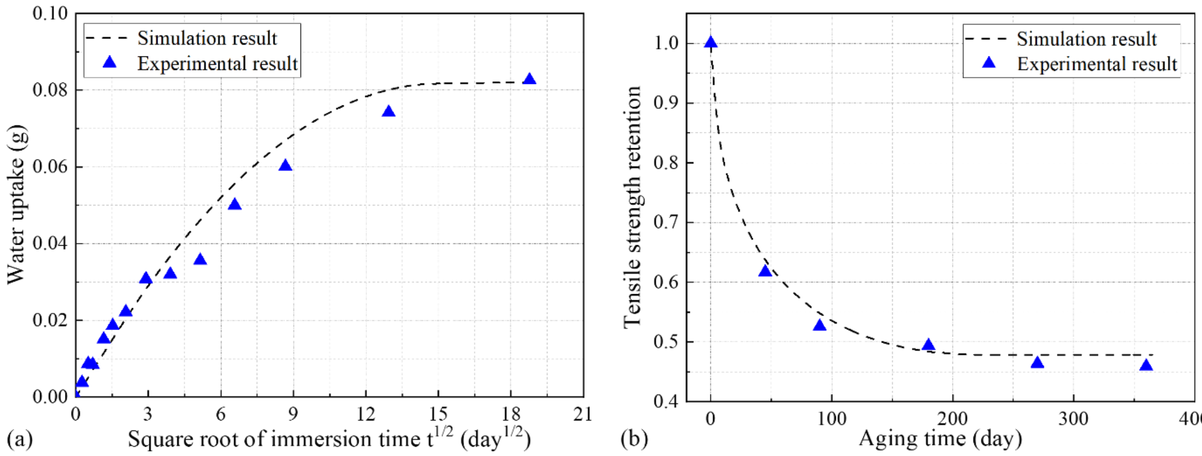

Figure 2. The performance of GFRP rebars in water at 60 °C for up to 12 months: (a) water uptake; (b) tensile strength retention.

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