Project number: T22-502/18-R

RESEARCH GRANTS COUNCIL
THEME-BASED RESEARCH SCHEME (TRS)

Completion Report on Funded Project

Project start date: 1 Jan 2019
Project completion date: 31 Dec 2024

1. Project Title:

Sustainable Marine Infrastructure Enabled by the Innovative Use of Seawater Sea-Sand Concrete and Fibre-Reinforced Polymer Composites

2. Names and Academic Affiliations of Project Team Members#

Project team member	Name / Post	Unit / Department / Institution	Average number of hours per week spent on this project in the whole project period
Project Coordinator (PC)	Prof. YU Tao# Professor	Civil and Environmental Engineering (CEE) / The Hong Kong Polytechnic University (PolyU)	12
Advisory Project Coordinator	TENG Jin-Guang# Chair Professor and President of PolyU	CEE / PolyU	6
Co-Principal Investigator(s)	DAI Jian-Guo#* Professor	Architectural and Civil Engineering / City University of Hong Kong (CityU)	12

	LEUNG Christopher K.Y. Professor	CEE / The Hong Kong University of Science and Technology (HKUST)	12
	LI Zongjin* Chair Professor	Department of Engineering Science / Macau University of Science and Technology	8
	NI Yi-Qing Chair Professor	CEE / PolyU	8
	POON Chi-sun Chair Professor	CEE / PolyU	12
	SANCHEZ Florence Professor	CEE / Vanderbilt University, USA	8
	SUN Tong Professor	School of Mathematics, Computer Science & Engineering / City University of London, UK	8
	WANG Sheng-Nian* Deputy Chief Engineer	CCCC Fourth Harbour Engineering Co., Ltd.	8
	ZHOU Limin* Chair Professor	School of System Design and Intelligent Manufacturing / Southern University of Science and Technology, China	8
Co-Investigator(s)	BUYUKOZTURK Oral Professor	CEE / Massachusetts Institute of Technology, USA	3
	CAO Jiannong Chair Professor	Computing / PolyU	4
	CHAN Tak-Ming* Associate Professor	Department of Civil Engineering / The University of Hong Kong	4
	DE BELIE Nele Professor	Structural Engineering / Ghent University	3
	DONG You* Associate Professor	CEE / PolyU	4
	FAN Zhi-Hong# Institute Director	CCCC Fourth Harbour Engineering Co., Ltd. China	4
	KELLER Thomas Professor	Structural Engineering / EPFL, Switzerland	3
	LAU Denvid* Associate Professor	Architectural and Civil Engineering / CityU	6
	LI Xiangdong Chair Professor	CEE / PolyU	4
	LIN Guan* Associate Professor	Department of Ocean Science and Engineering / Southern University of Science and Technology, China	6

	MAEKAWA Koichi Distinguished Professor	Graduate School of Engineering / The University of Tokyo, Japan	3
	NANNI Antonio Professor	Civil, Architectural and Environmental Engineering / University of Miami, USA	4
	SCHLANGEN H.E.J.G. (Erik) Professor	Structural Engineering / Delft University of Technology, The Netherlands	3
	SPENCER Billie F. Newmark Endowed Chair	CEE / University of Illinois at Urbana-Champaign	3
	XIA Yong Professor	CEE / PolyU	6
	YIN Jian-Hua Chair Professor	CEE / PolyU	6
	YOUNG Ben* Chair Professor	CEE / PolyU	4
	ZHENG Herbert Wei* CEO	Glorious Concrete (HK) Ltd. & Orientfunds Precast Ltd.	6
	ZHU Songye* Professor	CEE / PolyU	6
Collaborators			N.A.

\# *Please highlight the approved changes in the project team composition and quote the date when the RGC granted approval of such changes. For changes in the project team composition, please submit a separate request, together with the justification and the curriculum vitae of the new member(s), to the RGC three months prior to the intended effective date of the change.*

\# The RGC approved the following changes on 16 March 2020:
a. changing the role of Prof. TENG Jin-Guang in the project team from PC to Advisory PC, with his time spent on the project to be adjusted from 20 hours per week to 6 hours per week;
b. adding Prof. YU Tao to the project team to assume the post of PC with his time spent on the project to be 12 hours per week; and
c. changing the role of Prof. DAI Jian-Guo in the project team from Co-I to Co-PI with his time spent on the project to be adjusted from 8 hours per week to 12 hours per week.
Dr FAN Zhi-Hong joined the project team as a Co-I in replacement of Dr HU Ruo-Lin, a former Co-I who resigned from CCCC Fourth Harbour Engineering Institute Co., Ltd., China in November 2018. The RGC approved this change request on 18 August 2021.
Prof. KWAN KH Albert, Co-I from HKU retired on 30 June 2021 and his research work is taken up by Co-PI Prof. POON Chi-Sun (PolyU).

* Promotion or Changes in Affiliated Institutions of Team Members:
Prof. DAI Jian-Guo was promoted from Associate Professor to Professor on 1 July 2018.
Dr CHAN Tak-Ming was promoted from Assistant Professor to Associate Professor on 1 July 2019.
Dr DONG You was promoted from Assistant Professor to Associate Professor on 1 July 2022.
Dr LAU Denvid was promoted from Assistant Professor to Associate Professor on 1 July 2018.
Prof. YOUNG Ben joined PolyU from HKU on 21 December 2018. Prof YOUNG was

promoted from Professor to Chair Professor on 1 July 2021.
Prof. ZHU Song-Ye was promoted from Associate Professor to Professor on 1 July 2020.
Prof. ZHOU Li-Min left PolyU and joined Southern University of Science and Technology as Chair Professor on 11 May 2020.
Dr ZHENG W Herbert left Gammon Construction Ltd. and joined Glorious Concrete (HK) Ltd. & Orientfunds Precast Ltd. as CEO on 1 April 2021.
Mr WANG Sheng Nian changed his position from Chief Engineer to Deputy Chief Engineering in CCCC Fourth Harbour Engineering Co. Ltd. On 15 January 2019.
Dr LIN Guan left PolyU and joined Southern University of Science and Technology as an Associate Professor on 1 August 2022.
Prof. LI Zong-Jin joined Macau University of Science and Technology from University of Macau as a Chair Professor on 1 September 2022.
Prof. DAI Jian-Guo left PolyU and joined CityU on 1 August 2024. He continued to be a Co-PI of the project.
Prof. CHAN Tak-ming left PolyU and joined HKU on 1 September 2024. He continued to be a Co-I of the project.
Prof. YIN Jian-Hua's post title was changed from Chair Professor to Distinguished Research Professor on 19 September 2024.

3. Project Objectives

Summary of objectives addressed/achieved:

Objectives*	Percentage achieved	Remarks**
1. Develop the material structure models of SSC at nanometre and micrometre scales	100%	
2. Enhance the properties of SSC through microstructure modification	100%	
3. Relate the microstructure to the mechanical and durability properties of SSC	100%	
4. Develop innovative forms for FRP-SSC structural members with good ductility	100%	
5. Establish efficient and simple forms for connections between FRP bars, between components of a member (e.g., anchorage of FRP bars to SSC), and between members	100%	
6. Understand and model the behaviour of FRP-SSC members and systems with particular attention to the optimisation of their forms and formulation of design methods	100%	
7. Develop an optical fibre-based embeddable sensing system to enable simultaneous monitoring of various environmental parameters inside SSC	100%	
8. Develop PZT-based embeddable smart aggregates to enable active monitoring of material properties and micro-damage of SSC	100%	
9. Develop a hybrid FBG and BOTDA sensing system to monitor the performance of FRP components as well as debonding at interfaces between FRP and concrete	100%	
10. Develop a hybrid wireless communication system for data transmission and remote control	100%	
11. Understand the fundamental deterioration mechanisms of FRP, concrete and their interfaces	100%	
12. Develop multi-scale, multi-physics theoretical models for the long-term deterioration of FRP, concrete and their interfaces in mechanical properties	100%	
13. Formulate time-dependent constitutive models for SSC, FRP and their interfaces	100%	
14. Understand the deterioration mechanisms of mechanically-loaded FRP-SSC structural members through accelerated exposure tests in laboratory	100%	
15. Develop a predictive method for the accelerated deterioration of FRP-SSC structural members as observed in laboratory exposure tests	100%	
16. Verify/improve the predictive method using the field exposure tests of FRP-SSC structural members/frames	100%	

* *Please highlight the approved changes in objectives and quote the date when the RGC granted approval of such changes.*

** *Please provide reasons for significantly slower rate of progress than originally planned.*

6. Research Highlights and Outputs

6.1 What are the most exciting research accomplishments of the project?

This section presents the main research accomplishments of the project. Each is presented with (1) a summary paragraph; (2) highlights and findings; (3) representative figures (provided in Appendix 1). A list of journal papers including the accomplishment they contribute to is provided in Appendix 2, and the details of the work can be found in the respective papers.

Accomplishment 1: Multi-scale Elucidation of Hydration Mechanisms
This research represents a fundamental breakthrough in understanding how the complex ionic environments of seawater affect the hydration of cementitious materials. The team successfully elucidated the dissolution and precipitation mechanisms of hydrated cement in seawater, a subject previously insufficiently understood. The work has been published in over 30 papers in top-tier journals, such as *Cement and Concrete Research* and *Journal of the American Ceramic Society*. Furthermore, the findings have been presented at three international conferences, including one keynote speech (P3 in Section 7.2).

Discovery of Hydration Mechanisms: The team demonstrated that the high ionic strength of seawater significantly increases the dissolution of calcium and sulphate ions compared to freshwater, thereby enhancing the dissolution driving force of tricalcium silicate and tricalcium aluminate. This chemical environment fundamentally alters the hydration kinetics by elevating the nucleation rate constant while simultaneously reducing the growth rate constant. Consequently, the formation of nuclei on the clinker surface is accelerated, leading to a reaction mechanism that favours precipitation at numerous newly formed nucleation sites over the growth of hydration products at limited existing sites. (Figures T1-1 and T1-2; see Appendix 1)

Advanced Material Structure Analysis: Advanced characterization techniques, including small-angle neutron scattering (SANS), nanoindentation-energy dispersive X-ray spectroscopy, and porosity analysis, were conducted in an integrative manner. These revealed that Na^{+} and Ca^{2+} in seawater can enter mesopores in C-S-H particles, improving micromechanical performance. However, the presence of Mg^{2+} in seawater was identified as the primary cause of deleterious effects on the modulus and hardness of C-S-H. (Figures T1-3 to T1-5)

Multi-scale Simulation Framework: The team developed a comprehensive simulation framework comprising atomistic, meso-scale, and thermodynamic simulations. The atomistic simulations confirmed that $Mg^{2+} \rightarrow Ca^{2+}$ substitutions are possible in C-S-H and induce very modest volume variations and no drastic changes on the elastic properties, proving that experimentally observed swelling of the whole cement paste is not akin to the nano/atomistic scale but to a larger length scale. Meso-scale simulations further showed that ionic effects modify the Debye length (κ^{-1}) of C-S-H$_{particle}$ and dielectric constant (ε_r) of the C-S-H$_{gel}$ pore solution, leading to reduced porosity and increased cohesion. Thermodynamic modelling was successfully used to simulate the development of equilibrium phases in different C_3A reaction systems and the calcium dissolution thermodynamics of amorphous C-S-H and various C-S-H crystals in seawater, clarifying phase equilibria differences. (Figures T1-6 to T1-9)

Accomplishment 2: Innovative SSC Products
This research bridges fundamental science and societal needs, successfully translating theoretical findings into a suite of innovative SSC products. The team developed materials ranging from normal strength grades to ultra-high-performance and functionalized cementitious composites tailored for specialized needs. The work has been published in 23

papers in top-tier journals such as *Cement and Concrete Composites* and *Composites Part A*. Notably, six of the papers were recognized as Highly Cited Papers (H1 to H6 in Appendix 3), and one of the six was also a Hot Paper by Web of Science (H5), reflecting their profound influence in the field.

Normal- and high-strength SSC: The team developed a series of practical normal- and high-strength SSC mix proportions, including Grade 55 and Grade 80 SSC confirming to Hong Kong specifications. In addition, the team further optimized the workability and environmental sustainability of these mixes by incorporating waste glass powder (WGP), forming a low-carbon self-compacting SSC. The practicality of the developed SSC mix proportions has been validated through demonstration projects. (Figures T1-10)

Ultra-high-performance SSC (UHPSSC): The team developed UHPSSC that requires no coarse aggregate or high-temperature curing yet achieves a compressive strength exceeding 180 MPa, addressing the scarcity of coarse aggregates in remote marine environments. This material is particularly valuable for emergency infrastructure maintenance, as it may achieve compressive strengths exceeding 100 MPa within 24 hours. Furthermore, it can be combined with corrosion-free FRP to form lightweight, high-performance structures. (Figure T1-11)

Seawater Sea-Sand Engineered Cementitious Composites (SS-ECC): The team developed SS-ECC with ultra-high ductility, utilizing non-corrosive fibres, featuring a compressive strength exceeding 130 MPa, a tensile strength exceeding 8 MPa, and a tensile strain capacity of approximately 5%. (Figure T1-12)

Nano-materials modified cementitious composites: The team incorporated nano-materials such as graphene and high-structure nanocarbon black (nCB) to impart self-sensing capabilities to the concrete. A key innovation is the nCB-based ultra-high-performance seawater sea-sand concrete (nCB-UHPSSC), which exhibits outstanding mechanical properties (compressive strength >140 MPa) and workability (slump spread >160 mm) while possessing a stable, repeatable piezoresistive response with a high gauge factor exceeding 160, making it an economically viable solution for monitoring of marine infrastructure. (Figure T1-13)

Accomplishment 3: Innovative FRP Products for Marine Structures

The team developed a suite of innovative FRP products to address critical limitations in existing products, specifically regarding insufficient compressive behaviour, tensile ductility, and transverse shear resistance. This work has been published in 12 papers in top-tier journals, including *Engineering Structures* and *Composite Structures*, alongside presentations at three international conferences. The team has filed several patents about these innovative products (see Appendix 4). More importantly, these original technologies have inspired subsequent research by scholars, and one of these products (Patent 1-3 in Appendix 4) has been licenced to a start-up company founded by a team member (see Appendix 5).

FRP-UHPC hybrid rebars: The team developed an innovative form of steel-free hybrid rebars, in which a central FRP bar is confined by the surrounding UHPC and an external FRP tube. The FRP-UHPC hybrid rebars address the insufficient compressive behaviour of FRP bars. A variation of the hybrid rebar with a wavy-shape FRP tube has also been developed to enhance the bond with concrete. Compressive and pull-out tests were conducted to verify the performance of the hybrid rebar. The test results showed that the central FRP rebar is well-supported against bar buckling and fibre micro-buckling, and its compressive strength can be fully mobilized, leading to excellent ductility of the hybrid bar. (Figure T1-14)

Innovative FRP grid tubes: An innovative form of filament-wound FRP grid tubes was developed as a promising alternative to FRP spirals/stirrups due to their rigidity and ease of fabrication; the grid tubes may be used in various structural elements. Two types of FRP grid tubes were produced, including circular grid tubes for use as a confining device and rectangular grid tubes for use as shear reinforcement. Laboratory tests have been conducted which demonstrated the effectiveness of these FRP gird tubes in providing confinement to the concrete and in improving the shear capacity of the beams. (Figure T1-15)

<u>*Innovative FRP stirrups*</u>: The team has developed an innovative type of FRP stirrups. The stirrups are closed stripes sliced from a filament-wound FRP tube with a specially-designed shape. This new form eliminates the overlapping region in conventional FRP stirrups and significantly reduces the strength loss in the bending corners. The excellent performance of the novel stirrups has been demonstrated by laboratory tests. (Figure T1-16)

<u>*FRP rebar connectors:*</u> Two types of FRP rebar connectors were developed. The first type includes two inner FRP wedges and an outer FRP tube. The second type includes mainly a wavy-shaped FRP tube, which increases both the connecting performance and the bonding with the surrounding concrete. These connectors were successfully manufactured using the filament winding process, and combined laboratory tests and FE simulations demonstrated their satisfactory connecting performance and working mechanisms. (Figure T1-17)

<u>*Innovative FRP-coated steel rebars:*</u> The team explored the use of FRP as strong coating of steel rebar as an exploratory extension of the original scope of the project. The resulting rebars, named FRP-coated steel rebars (FCSRs), have a core steel rebar covered by a thin layer of FRP coating. FCSRs have corrosion-resistance comparable to stainless steel rebars with a cost less than 1/3 the latter. This product has been licensed to a start-up company, and a production line is being established for large-scale production. (Figure T1-18)

Accomplishment 4: Innovative Forms of FRP-SSC Structures

This research represents a transformative advancement in the field of hybrid structures incorporating FRP. The developed innovative structural components (columns, beams, slabs, and connections) successfully overcome the inherent brittleness of FRP, delivering exceptional ductility and superior load-bearing capacity. In addition, the team established numerical, analytical and design models for these structural components to guide their practical application. The work has been published in 20 papers in top-tier journals, including *Engineering Structures* and *Journal of Structural Engineering*. Furthermore, the findings have been presented at seven international conferences/workshops. In addition, the developed FRP-ECC-HSC column technology was awarded the HKIE Commendation Merit Award (R&D Category), and Gold Medal at the 49th International Exhibition of Inventions of Geneva (A1 and A2 in Appendix 6).

<u>*Innovative FRP-SSC columns:*</u> Two innovative forms of ductile FRP-SSC columns were developed. The first is concrete columns reinforced by FRP-UHPC hybrid rebars. A systematic experimental study, encompassing axial compression, eccentric compression, and cyclic axial/lateral loading tests, demonstrated that these columns exhibit ductility and load capacity superior to conventional FRP-reinforced concrete columns. The second is FRP-ECC-HSC composite columns, comprising an external FRP tube, a high-strength concrete (HSC) core, and an intermediate layer of engineered cementitious composite (ECC). Comprehensive experimental and analytical studies successfully validated the excellent ductility of the FRP-ECC-HSC composite column. (Figures T1-19 and T1-20)

<u>*Innovative FRP-SSC beams and slabs:*</u> Two forms of ductile FRP-SSC beams were developed. The first integrates ordinary FRP bars with additional GFRP spirals to confine the compressive concrete. The testing of large-scale beam specimens confirmed that this supplemental confinement imparts ductile flexural behaviour to the beams. The second utilizes a double-tube system comprising an outer filament-wound GFRP tube (for confinement), an inner pultruded

GFRP tube (for longitudinal reinforcement), and concrete infill joined by wavy FRP connectors. Bending tests successfully demonstrated the excellent structural performance of the novel form of beams. In addition, two forms of FRP-concrete hybrid slabs were developed utilizing FRP spirals of varying heights (half-section vs. full-section). Full-scale lab tests demonstrated that inclusion of spirals imparts excellent flexural ductility compared to control specimens. Complementing the experiments, 3D finite element (FE) modelling was conducted to simulate the FRP-SSC beams/slabs. These models captured test observations well, enabling optimized design of FRP-SSC beams/slabs. (Figures T1-21 to T1-26)

<u>*Innovative beam-column connections:*</u> Two types of innovative beam-column connections were developed. The first connects concrete-filled FRP tube columns to FRP profiles via stiffened FRP cleats and bolts; eight tests were conducted to identify failure mechanisms and optimize performance. The second, designed for FRP-reinforced concrete structures, strategically places FRP spirals in plastic hinge regions to significantly enhance structural ductility. Combined large-scale tests and FE modelling demonstrated the excellent ductility of these beam-column connections and enabled optimized design. (Figures T1-27 to T1-29)

Accomplishment 5: Novel Integrated Embeddable Chemical Sensing System
This research addresses the critical challenge associated with the real-time and in-situ health monitoring of innovative FRP-SSC structures in marine environments. The team successfully developed a novel integrated embeddable chemical sensing system based on optical fibre technology. This innovation overcomes the limitations of traditional destructive testing by enabling simultaneous, in-situ, and embeddable monitoring of durability indicators (chloride, sulphate, and pH) directly within the concrete matrix. The robustness of the sensing system was validated through successful deployment in field conditions at a wave wall in Lei Yue Mun, Hong Kong. The work has been published in over 40 papers in top-tier journals, including *Mechanical Systems and Signal Processing*, *Sensors*, and *ACTA Geotechnica*.

<u>*Fluorescence-Based Sensors:*</u> The team developed dual-ion (chloride and sulphate) high-sensitivity sensors utilizing fluorescence quenching mechanisms: first, a 3D-printed fluorescent-based sensor was engineered using quinine, where chloride ions induce fluorescence quenching, resulting in a measurable intensity decrease in spectrometers; second, a sulphate-sensitive fluorescent solution was converted into stable sensing films using cellulose acetate, allowing for successful fabrication of sulphate sensors. (Figures T1-30 to T1-32)

<u>*Integrated Sensing System Design:*</u> A fully integrated optical fibre-based embeddable sensing system was constructed to simultaneously monitor the internal chloride, sulphate, and pH of FRP-SSC structures. The design optimized critical manufacturing parameters, including the number of sensing layers, solution volume and drying times, housed within a custom 3D-printed enclosure. An Ocean LED Single Channel Touchscreen Controller was integrated to manage the light source precisely. The sensing system was first validated in the laboratory under simulated marine environment conditions and then validated through field deployment at a wave wall in Lei Yue Mun, Hong Kong. (Figures T1-33 to T1-34)

Accomplishment 6: A Hybrid Sensing Technology Framework
The team established a hybrid sensing technology framework that incorporates Electro-Mechanical Impedance (EMI) via PZT smart aggregates with distributed optical fibre sensing (OFDR/FBG). This framework achieves multi-dimensional monitoring capabilities, ranging from micro-environmental changes (temperature, humidity, local damage) to macro-structural behaviours (interfacial debonding, crack propagation), offering a holistic solution for evaluating the structural integrity of marine structures. The work has been published in 16 papers in top-tier journals, including *Smart Materials and Structures*, *Mechanical Systems and Signal Processing*, and *Structural Control & Health Monitoring*. Furthermore, the findings

have been presented at two international conferences/workshops.

Micro-environment Monitoring in SSC: The team developed a PZT-based micro-damage detection system comprising a terrestrial server, a portable impedance analyser, and embeddable smart aggregates (ESAs). The system supports remote configuration of impedance analysis parameters (e.g., voltage, resistance) via a custom user interface that runs on the terrestrial server for controlling portable impedance analyser remotely. Tests on SSC cubes established strong correlations between EMI and micro-environmental changes, specifically accounting for loading directions parallel (Type A) and perpendicular (Type B) to the PZT patch to ensure diagnostic accuracy. (Figures T1-35 to T1-38)

Macro-behaviour Monitoring of FRP-SSC Structures: The team developed a dual optic-fibre sensing technology for the accurate monitoring of FRP bar debonding and SSC cracking. Its effectiveness was demonstrated through three series of tests, including bending tests on FRP-concrete composite beams and push-out tests on FRP-concrete interfaces. To further understand experimental findings, numerical simulations were performed using zero-thickness cohesive elements. These simulations accurately captured the debonding process, ensuring the consistency of strain profiles at the FRP-concrete interface. (Figures T1-39 to T1-41)

Accomplishment 7: Solar-Powered 4G Wireless IoT Monitoring Platform with Edge Computing

The team established a robust solar-powered 4G wireless IoT monitoring platform equipped with edge computing capabilities to enable remote management of marine infrastructure. This platform represents a significant advancement in civil engineering digitalization, enabling real-time remote monitoring, data visualization, and system status management without reliance on grid power or cabled networks. The reliability of the platform is evidenced by its successful application in the Lei Yue Mun wave wall project. The work has been published in 9 papers in top-tier journals, including *IEEE TGCN, IEEE IoT Journal, ACM TKDD, and ACM IMWUT*.

IoT Architecture & Edge Computing: The platform employs distributed edge devices for local data preprocessing, utilizing Docker containers to manage data processing applications efficiently. A 4G gateway ensures seamless data transmission from edge nodes to remote servers. (Figure T1-42)

Remote Management Interface: A comprehensive cloud-based ecosystem was constructed, featuring a user interface (UI) that allows users to configure impedance analysis parameters (voltage, resistance) and visualize test data remotely in real-time. (Figure T1-43)

Demonstrated Resilience: The platform has been deployed several times in both field exposure tests and demonstration projects. It successfully simulated conditions where conventional power is unavailable, proving its viability for marine applications. (Figures T1-44 to T1-45)

Accomplishment 8: Comprehensive Experimental Durability Assessment of SSC, GFRP and Their Interfaces

The team conducted a comprehensive experimental program investigating the long-term degradation of SSC, GFRP, and their interfaces under various environmental conditions. This work provides a robust scientific basis as well as critical empirical data for engineering design and model development/verification. The work has been published in 12 papers in top-tier journals (e.g., *Cement and Concrete Composites*), and these papers have attracted over 400 citations according to Web of Science, reflecting their profound impact. Furthermore, the findings have been presented at five international conferences/workshops.

SSC Deterioration Characterization: Durability tests with focuses on carbonation and saline corrosion were conducted on SSC mixes with varying water/binder ratios (0.38 and 0.28).

Results indicated that while SSC initially showed high carbonation depth and strength loss compared to normal concrete, lowering the water/binder ratio significantly reduced this performance gap, identifying low w/b ratios as a critical design parameter for durable SSC structures. (Figures T1-46 to T1-47)

GFRP Deterioration Characterization: The team investigated the aging of GFRP bars in varying alkaline environments and temperatures (up to 60°C). Typical results indicated a decreasing degradation rate over time, reaching a constant threshold for long-term strength. A critical finding was that reducing the environmental pH from 13 to 11 quadruples the time required for 50% strength loss. This suggests a new direction for concrete mix design prioritizing low alkalinity, a concept validated using Magnesium Oxide (MgO) cement concrete which significantly slowed the degradation of FRP bars. Furthermore, the team utilized the Arrhenius approach to predict the degradation of GFRP bars under changing temperatures, and the predictions based on average annual temperatures align closely with those accounting for detailed temperature variations. Consequently, simplified strength retention curves applicable to different climatic zones were established for engineering design. (Figures T1-48 to T1-51)

GFRP-SSC Interfacial Deterioration Characterization: Pull-out tests were performed on GFRP rebars embedded in Grades C55 and C80 SSC under accelerated aging. The study confirmed that average bond stress at failure remains proportional to the square root of compressive strength across all aging scenarios. The measured data aligns closely with ACI440.1R-06 equations, validating the applicability of existing design codes to FRP-SSC structures. Furthermore, nano-indentation testing was established as a sensitive and viable technique for studying interfacial deterioration within fibre composites. (Figures T1-52 to T1-54)

Accomplishment 9: Molecular Dynamics (MD) and Coarse-Grained (CG) Simulations
The team pioneered the use of MD and CG simulations to provide fundamental scientific understanding of the degradation process of composite materials. This work successfully bridged the gap between the atomistic scale and the meso-scale by developing upscaling methods. These simulations provided unprecedented insights into the reaction mechanisms of glass fibres in alkaline environments and the molecular structure of resin crosslinking, laying the groundwork for the design of durable materials. The work has been published in 19 papers in top-tier journals, including *Nature Communications* and *Cement and Concrete Research*.

Bridging Scales with Coarse-Grained Modelling: MD and CG simulations were conducted to bridge disparate length scales. CG models were constructed based on atomistic data, utilizing a forcefield with a Mie functional form optimized via residual minimization to capture implicit environmental factors like water and chloride ions. (Figure T1-55)

Glass Fibre & Matrix Simulation: For glass fibres, the all-atom model accurately reflects the disordered aluminosilicate network (2000 Si, 480 Al, and 1180 Ca atoms), which was simplified into molecular functional units (SiO_4, AlO_4, and Ca^{2+}) in the CG model. This significantly reduced computational dimensions while retaining key physicochemical properties. For the vinyl ester (VE) matrix, a continuous single-chain growth method was adopted to simulate crosslinking, strictly enforcing head-to-tail region selectivity and precise monomer ratios to match commercial resin compositions. (Figures T1-56 to T1-58)

SSC and FRP-SSC Simulation: MD simulations utilizing Large-scale Atomic/Molecular Massively Parallel Simulator (LAMMPS) were conducted to elucidate seawater effects on SSC hydration, C-S-H mechanical behaviour, and pore mass transport. The CSHFF force field captured atomic interactions, while the ReaxFF potential modelled the cement paste-aggregate interface. ReaxFF parameters were optimized against quantum mechanics data to ensure high accuracy in representing inter- and intra-molecular interactions. These atomic models provide the foundation for upscaling to microscale models via coarse-grained techniques and homogenization. Additionally, simulations investigated FRP-SSC interface degradation under dry-wet conditions. These findings are integrated into a multiscale platform to reveal degradation mechanisms across different length scales. (Figures T1-59 and T1-61)

Accomplishment 10: Multi-Scale, Multi-Physics Material Deterioration Model
The team developed multiscale models for the degradation of SSC, GFRP and GFRP-SSC interface to relate long-term material strength to parameters at the mesoscale. This work uniquely integrates hydration kinetics, moisture transport, and mechanical damage approach to extend limited experimental data to more general engineering cases. The work has been published in four high-impact papers in top-tier journals, which have attracted over 100 citations according to *Web of Science*, reflecting their profound influence on the field. Furthermore, the findings have been presented at three international conferences/workshops.

<u>SSC Deterioration Model:</u> The team employed the multiscale approach developed by Co-I Maekawa to establish the SSC degradation model. At the lowest scale, the evolution of microstructure and porosity is obtained by simulating cement hydration kinetics and chemical transport, while accounting for the impact of porosity changes on water and chemical transport. Building upon this, shrinkage strain at different locations is calculated by simulating water migration, thereby deriving the internal stress distribution. Subsequently, a mechanical damage model was applied to determine material mechanical behaviour under the coupled effects of applied loading and shrinkage/creep. When accounting for continuous chemical penetration, the long-term behaviour of SSC could be extrapolated through corresponding changes in microstructure and porosity. (Figure T1-62)

<u>GFRP Deterioration Model:</u> The team developed the GFRP deterioration by considering moisture diffusion and local fibre deterioration. Using the Finite Element Method and an assumed 30% saturation threshold for fibre deterioration to occur, the model successfully predicts water absorption and strength retention, showing strong agreement with experimental results. For GFRP in alkaline environments, a sink term (kC^m) is introduced to the diffusion equation to reflect chemical reactions. The resulting unified model accounts for coupled water and alkali effects, providing upper/lower bounds of strength retention across various temperatures that match test results. It also predicts degradation for varying rebar sizes and geometries, eliminating the need for exhaustive environmental testing for every specific configuration, significantly streamlining the design process. (Figures T1-63 to T1-66)

<u>GFRP-SSC Interfacial Deterioration Model:</u> The team adopted the modified BPE model to fit the measured bond-slip curves of the aged GFRP-SSC interface. Afterward, the identified model is used as the interfacial constitutive model of a 3D finite element (FE) model to gain more insight into GFRP-SSC interfacial behaviour deterioration. In addition, the FE model utilizes a nonlinear concrete damage plasticity model and accounts for the detailed geometry of the GFRP rebar. The FE model predictions agree well with test results for validation dataset, it is expected that that the FE model can be employed for predicting degradation of bond when concrete properties change under various environmental exposures. (Figures T1-67)

Accomplishment 11: Multi-scale Modelling Platform for FRP-SSC Structures
A first-of-its-kind platform has been developed to predict the long-term performance of FRP-SSC structures. This platform scientifically articulates material degradation processes across various scales from molecular, micro, meso, to macro and their impact on structural performance. Additionally, it provides a robust tool to support the practical design of FRP-SSC structures. The relevant research outcomes have been disseminated through 20 top-tier

international journal publications, including an Editor's Choice award from the *ASCE Journal of Composites for Construction*. Additionally, the work has been acknowledged with the International Collaboration Award from the Japanese Society of Civil Engineers (JSCE) (see Appendix 6), and its impact is evident in international codes of practice, such as ISO 14484 "Performance Guidelines for the Design of Concrete Structures Using FRP Materials".

Modelling platform: A framework was developed by extending the multiple scale simulation platform "DuCOM-COM3" to FRP-SSC structures. The platform was first modified to predict the long-term structural performance of FRP-reinforced normal concrete beams under wet-dry cycling of NaCl solution, considering the mass transport process and material/interface degradations. The geochemical subroutine PHREEQC was integrated into the platform to consider the equilibrium state among solids, pore solution and gases. By adopting a deterioration model of FRP bars, and simulating the deterioration of FRP-to-normal concrete interface through setting different levels of tension-stiffening degradation, the analysis results are found to be in a general good agreement with the existing experimental data. Furthermore, by incorporating microstructure-based stress-strain, mass transport and long-term shrinkage models for SSC, the simulation platform can approximately predict the time-dependent behaviour and the failure modes of FRP-SSC structural members after environmental exposure, which were tested in this project for model validation. (Figures T1-68 and T1-69)

Accomplishment 12: Field Exposure Tests, Demonstration Projects, and Mock-up Frame
This research has moved beyond the laboratory through an extensive field test programme and real-world demonstrations. The innovative materials, sensors, and structural forms developed in this project have been successfully implemented in multiple demonstration projects and a three-storey mock-up frame that integrates a combination of the developed technologies.

Field exposure tests: Four series of field exposure tests were conducted, providing valuable data demonstrating the real-world performance of FRP-SSC structures and validating the simulation models. The four series of tests involved over 3800 specimens of various types, covering glass fibres, GFRP bars, profiles and rings, hybrid FRP rebars, FRP-coated steel rebars, SSC cubes, sensors, FRP-SSC bonded joints, SSC-filled FRP tubes, and FRP-SSC beams. Environment conditions covered atmospheric zone, splash zone, tidal zone, and underwater zone. During the project period, mechanical tests were conducted on specimens exposed for up to four years, while some specimens will be left on-site for extended exposure and testing beyond the project period. (Figures T1-70 and T1-71)

Demonstration Projects: The team successfully completed four demonstration projects: (1) Exposure Station (Lvsi Port, Nantong, Jiangsu): this project showcased a seawater-mixed concrete mix and slabs reinforced with FRP bars and stirrups. A two-storey reinforced concrete frame incorporating these slabs was constructed and currently functions as a long-term exposure station, see Figure T1-72; (2) Smart Road Pavement (Shatin Sewage Treatment Works, Hong Kong): this project demonstrated three key technologies, i.e., a low-carbon self-compacting SSC mix, FRP-coated dowel bars, and smart sensors for structural health monitoring. A smart pavement system comprising 16 precast concrete slabs was constructed and remains fully operational and in good condition, see Figure T1-73; (3) Wave Walls (Lei Yue Mun, Hong Kong): this project demonstrated the application of innovative structural forms in coastal defence. Two 10-meter-long wave wall sections were constructed: one utilizing SSC reinforced by GFRP bars, and the other utilizing conventional concrete reinforced by FRP-coated steel bars, see Figure T1-74; (4) Precast Pier Slabs (Lai Chi Chong, Hong Kong): this demonstration focused on precast slabs utilizing developed FRP-SSC technologies. Four distinct slab types were precast and installed at the pier for comparative performance monitoring, i.e., an SSC slab reinforced with GFRP bars, a normal concrete slab reinforced with GFRP bars, a conventional steel-reinforced concrete slab, and a steel-reinforced slab incorporating FRP mesh for crack control, see Figure T1-75. In addition, the advanced fibre optic sensing technique developed by the project team was successfully used in the Peanut-Shaped Cofferdam (Trunk Road T2 and Cha Kwo Ling Tunnel project) to investigate the behaviour of three diaphragm wall panels of a 38-meter-deep twin circular peanut-shaped cofferdam, see Figure T1-76.

<u>Mock-up Frame:</u> A three-storey FRP-SSC mock-up frame were constructed on Guishan Island, Zhuhai, serving as a marine exposure platform. The frame has a length of 3.7 m, a width of 2 m, and a height of 7.8 m. Within this frame, the team integrated and demonstrated a suite of developed technologies, including a self-compacting SSC mix design, novel FRP products (e.g., hybrid FRP rebars, FRP-coated rebars), novel FRP-SSC structural elements (columns, beams, and slabs), and novel structural health monitoring smart sensors and data transmission technologies. The frame has maintained stable operation throughout the construction and service phases, meeting expected technical specifications. It offers an innovative solution for achieving long-term, corrosion-free operation of offshore structures (Figure T1-77).

6.2 What was the added value of the TRS funding, rather than standard project grant funding?

The transformative outcomes of this project could not have been achieved through funding schemes such as the General Research Fund (GRF) or the Collaborative Research Fund (CRF). The Theme-based Research Scheme (TRS) provided unique added value in three critical dimensions that were essential for the success of this large-scale, paradigm-shifting initiative:

(1) Enabling Long-Term Exploration of Complex Systems Through Substantial Funding
Unlike the GRF, which typically supports short-term, narrowly focused studies, the TRS funding provides substantial resources over a duration of five years (this project was extended to six years). The scale and stability of funding allowed the team to undertake the pioneering challenge of replacing conventional steel-reinforced concrete with innovative FRP-SSC structures. The first key added value of the TRS was its structural capacity to support an ambitious, integrated research program. It enabled a holistic research scope, ranging from molecular dynamics and materials science to structural design and full-scale application, that would otherwise have been fragmented and disjointed if pursued through multiple smaller GRF or CRF grants. The six-year project period provided the necessary continuity not only to resolve fundamental scientific issues but also to conduct field exposure tests and to plan and conduct full-scale demonstration projects. This progression from foundational science to tangible engineering validation is a core achievement facilitated by the TRS.

(2) Facilitating Deep Multidisciplinary Integration
While the CRF encourages collaboration, it generally operates on a smaller scale. The second key added value of the TRS was its capacity to merge diverse expertise across materials science, structural engineering, and chemistry into a singular, coherent program dedicated to developing the complete FRP-SSC system. This project-level synthesis, fundamental for innovating an entirely new material-structural solution, goes beyond standard collaborative grants. Furthermore, the TRS facilitated a global platform, uniting leading international experts from various disciplines to develop new-generation marine infrastructure.

(3) Bridging the Gap from Basic Science to Strategic Societal Impact
Standard funding schemes often prioritize academic metrics, such as publications, over practical utility. In contrast, the TRS explicitly focuses on research "themes" of strategic importance to Hong Kong's long-term development. The third key added value was that this

mandate drove the team to go beyond purely theoretical outputs. It directly promoted the translation of fundamental research into tangible solutions for Hong Kong, specifically the development of next-generation sustainable marine infrastructure (i.e., FRP-SSC structures). The scheme also facilitated the effective engagement with government departments and industry partners, ensuring that scientific breakthroughs were translated into practical products and construction technologies that deliver direct benefits to the local community. This translation is evidenced by the several demonstration projects completed within this TRS project, which showcase the developed technologies in real-world applications.

In summary, the TRS provided the essential scale, time, and strategic mandate required to transform a scientific concept into a viable engineering reality. This holistic achievement would have been impossible under the constraints of other funding schemes such as the GRF or CRF.

6.3 If the project has not met its original objectives, why?

N/A

6.4 (a) Please provide details of each peer-reviewed journal publication arising directly from this project by completing the table at **Annex** *(one for each publication)*. See the Annexes.

(b) Please provide details of recognised international conference(s) in which paper(s) related to this project was/were delivered by completing the following table:
(Please attach a copy of each conference abstract)

Month/Year/ Place (Accomplishment)	Title	Conference name	Submitted to the RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of the RGC *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Jan/2020/ Haifa, Israel	Effect of seawater on the hydration of tricalcium silicate	The 3rd International RILEM Workshop on Concrete Durability and Service Life Planning (ConcreteLife 2020)	2025	Yes	Yes	Yes
Jan/2021/ Hong Kong, China	Effect of concrete alkalinity and porosity on the durability of GFRP rebars*	The 4th International Workshop on Seawater Sea-sand Concrete (SSC) Structures Reinforced with FRP Composites	2025	Yes	Yes	Yes
Mar/2022/ London, UK	Experimental investigation on axial compressive behaviour of novel FRP-ECC-HSC composite stub column*	The 24th Young Researchers Conference of the Institution of Structural Engineers (IStructE)	2025	Yes	-	Yes
Jan/2022/ Hong Kong, China	Experimental and numerical research on the diffusion-degradation process of GFRP composite*	The 5th International Workshop on Seawater Sea-sand Concrete (SSC) Structures Reinforced with FRP Composites	2025	Yes	-	Yes

Month/Year/ Place (Accomplishment)	Title	Conference name	Submitted to the RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of the RGC *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Sep/2022/ Kyoto, Japan	Hydration kinetics of alite pastes mixed with seawater and single salt solutions*	The 76th RILEM Annual Week 2022 and International Conference on Regeneration and Conservation of Structures	2025	Yes	-	Yes
Dec/2022/ Shenzhen, China	Diffusion of saline contents in GFRP rebar and induced GFRP degradation	The Joint Conference of the 15th International Symposium on Fiber Reinforced Polymers for Reinforced Concrete Structures (FRPRCS-15) & the 8th Asia-Pacific Conference on Fiber Reinforced Polymers in Structures (APFIS-2022)	2025	Yes	Yes	Yes
Dec/2022/ Shenzhen, China	FRP-concrete-steel double skin tubular members filled with seawater sea-sand concrete: a feasibility study	The Joint Conference of the 15th International Symposium on Fiber Reinforced Polymers for Reinforced Concrete Structures (FRPRCS-15) & the 8th Asia-Pacific Conference on Fiber Reinforced Polymers in Structures (APFIS-2022)	2025	Yes	Yes	Yes
Dec/2022/ Shenzhen, China	FRP-coated steel rebars for the reinforcement of concrete structures: concept, manufacturing process, corrosion resistance and bond performance	The Joint Conference of the 15th International Symposium on Fiber Reinforced Polymers for Reinforced Concrete Structures (FRPRCS-15) & the 8th Asia-Pacific Conference on Fiber Reinforced Polymers in Structures (APFIS-2022)	2025	Yes	Yes	Yes
Mar/2023/ Shenzhen, China	Effect of seawater sea-sand concrete on tensile strength reduction of GFRP rebars and corresponding degradation mechanism*	The 4th Asian Concrete Federation (ACF) Symposium on Emerging Technologies for Structural Longevity (ACF2023 ETSL)	2025	Yes	-	Yes
July/2023 / Arlington, Virginia	Axial cyclic behavior of FRP confined seawater sea-sand concrete piles	Geo-Risk 2023	2025	Yes	Yes	Yes
July/2023/ Rio de Janeiro, Brazil	Cyclic compressive stress-strain model for FRP-confined engineered cementitious composites (ECC)	The 11th International Conference on Fiber-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE 2023)	2025	Yes	Yes	Yes
Nov - Dec /2023/ Sydney, Australia	Tests of thin-walled pultruded GFRP beam-to-column joints	The 9th International Conference on Thin-Walled Structures (ICTWS13)	2025	Yes	Yes	Yes

Month/Year/ Place (Accomplishment)	Title	Conference name	Submitted to the RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of the RGC *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Feb/2024/ Shenzhen, China	Applicability of nanoindentation technique for the characterization of interfacial degradation of GFRP in alkaline environment*	The 7th International Workshop on Seawater Sea-sand Concrete (SSC) Structures Reinforced with FRP Composites	2025	Yes	-	Yes
Feb/2024/ Shenzhen, China	Multiscale modelling of GFRP-reinforced reactive magnesia concrete (GFRP-RMC): mechanical properties and long-term durability*	The 7th International Workshop on Seawater Sea-sand Concrete (SSC) Structures Reinforced with FRP Composites	2025	Yes	-	Yes
Mar/2024/ New Orleans, USA	Sustainable marine infrastructure enabled by the innovative use of seawater sea-sand concrete and fiber-reinforced polymer*	The 16th International Symposium on Fiber-Reinforced Polymer Reinforcement for Concrete Structures (FRPRCS-16)	2025	Yes	-	Yes
Sep/2024/ Dresden, Germany	Tensile and compressive performance of high-strength Engineered Cementitious Composites (ECC) with seawater and sea-sand*	The 11th RILEM-fib International Symposium on Fibre Reinforced Concrete (BEFIB2020)	2025	Yes	Yes	Yes
Nov/2024/ Guangzhou, China	Structural behaviour of FRP-ECC-HSC composite columns	The 1st International Conference on Engineering Structures (ICES 2024)	2025	Yes	Yes	Yes
Dec/2024/ Adelaide, Australia	Valorisation of Recycled Macro recycled macro fibres as Discrete Reinforcement in Seawater Sea-Sand Concrete*	The 9th Asia Pacific Conference on FRP in Structures (APFIS 2024)	2025	Yes	-	Yes
Dec/2024/ Adelaide, Australia	FRP Debonding Detection via Local and Global Approaches*	The 9th Asia Pacific Conference on FRP in Structures (APFIS 2024)	2025	Yes	-	Yes
Dec/2024/ Adelaide, Australia	Evaporation of Water from NaCl Solution Confined in C-S-H gel Pore Using MD Study: Effects of Ca/Si Ratio	The 9th Asia Pacific Conference on FRP in Structures (APFIS 2024)	2025	Yes	Yes	Yes
Dec/2024/ Adelaide, Australia	On Developing Filament Wound FRP Grid Tube*	The 9th Asia Pacific Conference on FRP in Structures (APFIS 2024)	2025	Yes	-	Yes
Dec/2024/ Adelaide, Australia	Biomimetic graphene oxide-layered double hydroxide heterostructures for enhanced chloride adsorption and corrosion resistance in marine concrete*	The 9th Asia Pacific Conference on FRP in Structures (APFIS 2024)	2025	Yes	-	Yes
Dec/2024/ Adelaide, Australia	Hydration and hardening properties of seawater-mixed cementitious materials: discussion from C_3S and C_3A phases*	The 9th Asia Pacific Conference on FRP in Structures (APFIS 2024)	2025	Yes	-	Yes

Month/Year/ Place (Accomplishment)	Title	Conference name	Submitted to the RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of the RGC *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Dec/2024/ Adelaide, Australia	FBG-based relative humidity sensing system and relative humidity prediction with machine learning*	The 9th Asia Pacific Conference on FRP in Structures (APFIS 2024)	2025	Yes	-	Yes
Dec/2024/ Adelaide, Australia	On developing a time-dependent bond stress-slip model for GFRP bars in seawater sea-sand concrete*	The 9th Asia Pacific Conference on FRP in Structures (APFIS 2024)	2025	Yes	-	Yes
Dec/2024/ Adelaide, Australia	Precast seawater and sea-sand concrete columns reinforced with fiber-reinforced polymer (FRP) composites*	The 9th Asia Pacific Conference on FRP in Structures (APFIS 2024)	2025	Yes	-	Yes

Note: 1. The conference abstracts are available in Appendix 7.
2. The above table includes presentations delivered at a conference/workshop with an abstract but without a full paper. These presentations are marked with an asterisk (*). The conference abstracts typically do not have an acknowledgement section.

(c) RGC funding should have been acknowledged in all publication(s)/conference papers listed in (a) and (b) above. If no acknowledgement has been made in any of the publications/ papers, please indicate and provide explanations.
N/A

6.5 To what extent this project has strengthened inter-institutional collaborations and other partnerships?

The project has significantly strengthened inter-institutional collaborations, demonstrated through sustained academic partnerships with global experts, formalized inter-institutional agreements, and translational partnerships with key industry and government bodies. These collaborations are exemplified by the following activities.

Fundamental mechanisms of SSC: Collaboration among Co-PI Poon (PolyU), Co-PI Sanchez (Vanderbilt University), and Co-PI Li (Macau University of Science and Technology) on MD simulation and material properties. Co-PI Poon also maintains a collaborative research partnership with Prof. Roland J.M. Pellenq (CNRS/Université of Montpellier).

Innovative FRP-SSC members: Collaboration between PC Yu's team (PolyU) and Co-I Keller (EPFL) on hybrid FRP-SSC beams, including a research visit by a PolyU PhD student (Mr. Jiaming Zhu) under PC Yu's supervision to EPFL.

Development of novel sensors: Collaboration between Co-PI Ni (PolyU) and Co-PI Sun (City University of London) on optical fiber-based sensors, supported by a formal signed agreement between CNERC-Rail at PolyU and City University of London.

Time-dependent constitutive behaviour of SSC: Joint work by Co-PI Leung (HKUST), Co-PI Li (Macau University of Science and Technology), and Co-PI Sanchez (Vanderbilt University) with Co-I Maekawa (Yokohama National University) on modelling SSC deterioration; collaboration between Co-I Lau (CityU) and Co-I Buyukozturk (MIT) on MD simulations.

Predictive method for performance of FRP-SSC members: Work by Co-PI Dai (PolyU) with Co-I Maekawa (Yokohama National University) on the simulation of FRP-SSC structural members, involving incorporation of the thermo-physics and mechanics of SSC into the simulation platform developed by Co-I Maekawa.

Field exposure tests, mock-up frame and demonstration projects: Partnership with Co-I Zheng for raw materials and a casting site of SSC; collaboration with Co-PI Wang (CCCC) on field exposure tests and a mock-up frame; collaboration with the Civil Engineering and Development Department (CEDD) of Hong Kong SAR on demonstration projects.

6.6 Research students trained (registration/awards):

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Yanjie Sun	PhD	31/08/2018	15/12/2022^^
Siqi Ding	PhD	01/09/2016	15/03/2021^^
Lingyu Xu	PhD	02/08/2019	31/12/2022^^
Xingquan Wang	PhD	01/09/2018	03/10/2022^^
Peng Wang	PhD	01/02/2019	31/08/2022^^
Yamei Cai	PhD	28/08/2019	30/06/2024^^
Lun Wing Lam	PhD	29/08/2019	31/08/2025^^
Linyuwen Ke	PhD	01/09/2019	31/08/2023^^
Yiwen Zhang	PhD	17/08/2017	30/04/2024^^
Xiong Sha	PhD	26/08/2019	31/03/2025^^
Malik Numan	PhD	01/09/2019	26/02/2024^^
Qianyi Chen	PhD	01/09/2019	31/01/2024^^
Zhihao Hao*	PhD	27/08/2019	29/02/2024^^
Zhiyu Xia#	PhD	02/09/2019	31/03/2025^^
Abasal Hussain	PhD	30/08/2020	28/02/2025^^
Ting Yui Wong	PhD	01/09/2020	26/08/2025^
Xinyun Li	PhD	05/08/2019	18/05/2025^
Fuhao Deng*	PhD	24/08/2019	31/05/2025^^
Ruilong Li	PhD	30/08/2019	10/12/2025^
Xi Li	PhD	30/08/2019	31/12/2026**
Jiaming Zhu	PhD	02/09/2020	30/04/2026**
Chuying Cui*	PhD	03/09/2020	29/08/2025^
Tianhui Lu*	PhD	09/09/2020	31/08/2024^^
Mingxuan Ye*	PhD	15/09/2020	Withdrawn due to health issues
Zhen Lin	PhD	31/08/2020	30/04/2026**
Qian Wu*	PhD	02/09/2020	31/10/2024^^
Shuxian Ding	PhD	01/09/2020	31/12/2026**
Dong Han	PhD	30/08/2021	30/04/2026**
Jiajie Cai	PhD	30/08/2021	30/04/2026**
Junjie Zhang	PhD	30/08/2021	30/11/2025^^
Pochang Liu	PhD	30/08/2021	30/04/2026**
Umar Hayat	PhD	01/01/2022	03/11/2025^

Note: * Joint PhD Program with Southern University of Science and Technology (SUSTech); # Joint PhD Program with Zhejiang University; ^ date of thesis submission; ^^ date of graduation; ** expected date of thesis submission.

6.7 Specific products (e.g. software or netware, instruments or equipment developed):

The team developed three practical SSC mix proportions, including Grade 55 SSC, Grade 80 SSC, Low-carbon self-compaction SSC mix proportions. These mix proportions have been implemented in field demonstration projects and the construction of a mock-up frame.

The team also developed numerous innovative concrete products, including ultra-high-performance SSC (UHPSSC), seawater Sea-Sand Engineered Cementitious Composites (SS-ECC), Nanocabon black(nCB)-based self-sensing ultra-high-performance seawater sea-sand concrete (nCB-UHPSSC), strain-hardening ultra-high-performance geopolymer concrete (SH-UHPGC), seawater sea-sand Engineered Geopolymer Composites (SS-EGC).

The team also developed a lot of innovative structural materials and components to support the research and application of FRP-SSC structures, including FRP-UHPC hybrid rebars, FRP grid tubes, innovative FRP stirrups, FRP rebar connectors, FRP-coated steel rebars, wavy FRP tubes, two forms of ductile FRP-SSC columns, two forms of ductile FRP-SSC beams, two forms of FRP-SSC slabs, two forms of beam-column connections.

The team also developed a series of sensing technologies for structural health monitoring of FRP-SSC structures, including optical fibre-based pH, humidity, chloride, and sulphate sensors, PZT-based smart aggregates and a portable impedance analyser for the smart aggregates, a hybrid FBG and BOTDA sensing system enabling FRP-to-concrete interfacial debonding and SSC cracking monitoring, a robust solar-powered 4G wireless IoT monitoring platform.

The team established numerous methods/models covering various aspects of FRP-SSC structures, including a method for production of low-cost flash graphene from carbon black, a rapid method for assessing the Alkali-silica reaction (ASR) risk in SSC, a 3D plasticity constitutive model for accurate simulation of confined concrete, a vibration-based FRP debonding detection method using a Q-learning evolutionary algorithm, a layer-by-layer assembly method of polyelectrolytes-wrapped multi-walled carbon nanotubes on long period fibre grating sensors, an in-situ method for synthesizing carbon nanotubes on cement, a cementitious capping material and method for high-strength and ultra-high-strength concrete, a method for utilising porous aggregates for carbon sequestration in concrete, etc.

In addition, a walk-in environmental chamber (4.5 m × 7 m × 3 m) has been specifically designed and manufactured for this project.

6.8 Other education activities and/or training programmes developed:

An annual international workshop on seawater sea-sand concrete structures reinforced with FRP composites (FRP-SSC Workshop) were successfully organized for six times (Dec 2018, Jan 2020, Jan 2021, Jan 2022, Feb 2023, and Feb 2024). An Industry Forum/Session was organized in the last two of the FRP-SSC Workshop series to enhance awareness of the emerging technology among the relevant industries. Furthermore, a two-day short course was delivered to a group of engineers from CEDD on FRP composites for construction in 2021. In collaboration with CEDD, another workshop was delivered in 2025 on the newly developed Hong Kong Design Guidelines for the Use of FRP for Marine Structures. In addition, a number of undergraduate final year project (FYP) students have been trained in the project.

6.9 Please highlight any deliverables indicated in the project implementation timetable endorsed by the RGC which have not been covered or achieved as per sections 6.1 to 6.8 above, and explain/ elaborate.
Nil.

Project Management

6.10 Please elaborate how the PC has played his/her role in coordinating and managing the project.

Prof. Jin-Guang Teng was the PC from January 2019 to March 2020. RGC approved revision of Prof. Jin-Guang Teng's role from PC to Advisory PC, and the addition of Prof. Tao Yu to the project as PC and Task 2 leader on 16/3/2020.

PC Yu and Advisory PC Teng managed and coordinated the project mainly via the Management Committee. During the project period, Advisory PC Teng organized and chaired the Launching Ceremony, three Management Committee Meetings (MCMs) and one External Advisory Board (EAB) Meeting, while PC Yu organized and chaired nine MCMs and four EAB Meetings (see Appendix 8 and 9). PC Yu also chaired the fourth, fifth and sixth FRP-SSC Workshop and co-chaired the seventh FRP-SSC Workshop (see Appendix 8). PC Yu maintained close contact with the key team members via email, phone, and/or face-to-face meeting, and gave comments and feedback to the task leaders by monitoring the research direction and research progress of the task. Within the team of PC Yu and Advisory PC Teng, there were two research assistant professors and several postdoctoral fellows who assisted them in managing the project. PC Yu also held regular meetings with research staff members in his team who worked on the project.

PC Yu led the efforts of setting up a local Industry Advisory Committee (IAC), which is composed of seven committee members from various sectors of the local industry. The IAC was formed to facilitate the technology transfer activities including field demonstration projects. PC Yu organized four IAC meetings, and the meeting minutes are also attached in Appendix 9. The IAC members made contribution to the technology application, promotion, and transfer.

Furthermore, PC Yu played an important role in coordinating the cross-task collaboration on field exposure tests, demonstration projects and mock-up frame. Under his leadership, multiple demonstration projects on the use of FRP and SSC, along with a mock-up frame integrating the research outcomes of the project, have been successfully completed. These projects involved close collaboration of team members from various tasks (for the concrete mix, structural design, for the monitoring system, respectively) and external parties (for logistics and site supervision).

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7. Awards and Recognition

7.1 Have any research grants been awarded that are directly attributable to the results obtained from this project?

(1) PC Yu secured a research grant for a project under the Guangdong-Hong Kong Technology Cooperation Funding Scheme (TCFS) of the Innovation and Technology Fund (ITF); the project title is "*Precast Seawater and Sea-Sand Self-Compacting Concrete (SSSW-SCC) Structures Reinforced with Fiber-Reinforced Polymer (FRP) Composites* (GHP/041/20GD)", and the funding amount is HKD1.52 million.

(2) PC Yu secured a research grant for a project under the National Natural Science Foundation of China/RGC Collaborative Research Scheme; the project title is "*FRP-Reinforced concrete structures for marine environments: material and structural innovations for ductility enhancement and prefabricated construction*", and the funding amount is HKD3.57 million.

(3) Co-PI Poon secured a research project funded by the Lantau Conservation Fund; the project title is "*Enhancement of marine biodiversity and ecosystem functioning along Lantau eco-shoreline with low-pH sea-sand seawater eco-engineered seawall panels*", and the funding amount is HKD2.27 million.

(4) Co-PI Poon secured a research project funded by the Green Tech Fund; the project title is "*Low-carbon Transformation of Construction Materials Using Waste Glass*", and the funding amount is HK$4.60 million.

(5) Co-I Li Xiangdong secured a research grant funded by the Green Tech Fund; the project title is

"*Marine Self-Healing Concrete with Biomineralization-Enhanced Construction Waste for Long-Term Decarbonisation*", and the funding amount is HK$6.025 million.

(6) A team led by Co-I Xia, including many members from this TRS project, secured funding from the Department of Science and Technology of Guangdong Province (GDSTC) for *the Guangdong-Hong Kong Joint Laboratory for Marine Infrastructure*; the funding amount is HKD 21.7 million.

(7) A team led by Co-I Li Xiangdong, including many members from this TRS project, secured funding from the Ministry of Science and Technology (MOST) of the People's Republic of China for the State Key Laboratory of Climate Resilience for Coastal Cities (SKL-CRCC), which is jointly held by The Hong Kong University of Science and Technology (HKUST) and The Hong Kong Polytechnic University (PolyU); the funding amount to PolyU is HKD 12.8 million per year.

(8) Co-PI Cao secured an RGC Theme-based Research Scheme (TRS) project; the project title is "High-performance Collaborative Edge Computing Enabling Smart City Applications: Frameworks and Methodologies", and the funding amount is HKD 50.821 million.

(9) Co-I Zhu secured an RGC Research Impact Fund (RIF) project; the project title is "Digital twin-enabled intelligent assessment and maintenance of offshore wind turbine structures in a life-cycle context", and the funding amount is HKD 4.97 million.

*Note: Items (6), (7), (8) and (9) are partially attributable to the results obtained from the project.

7.2 Have any project team members participated as invited speakers in or organisers of international conferences as a result of this project?

<u>Conference Organization</u>

(1) PC Yu and Advisory PC Teng organized six times *the International Workshop on Seawater Sea-sand Concrete (SSC) Structures Reinforced with FRP Composites*. Many team members participated as invited speakers to present the results of this project.

(2) Co-I Prof. Antonio Nanni organized the ACI Webinar *Seawater-Mixed Concrete: A New Class of Sustainable Concrete*.

(4) PC Yu and Co-PI Dai served as Co-Chairs of Organizational Committee of *the 15th International Conference on Fibre-Reinforced Polymers for Reinforced Concrete Structures (FRPRCS-15) and the 8th Asia-Pacific Conference on FRP in Structures (APFIS-2022)*.

(5) Co-PI Dai served as a Co-Chair of *the 4th Asian Concrete Federation Symposium on Emerging Technologies for Structural Longevity (ACF2023_ETSL)*.

(6) PC YU and Dr. XIANG Yu co-chaired a mini-symposium on seawater sea-sand concrete (SSC) structures reinforced with FRP composites at *The Ninth-Asia Pacific Conference on FRP in Structures* (APFIS 2024) held on 8-11 December 2024 at Adelaide, Australia.

<u>Invited/Keynote Presentations</u>

(P1) Teng, J.G. and Yu, T. (2021). "Sustainable marine infrastructure enabled by the innovative use of seawater sea-sand concrete (SSC) and fibre-reinforced polymer (FRP) composites", Keynote Speech, delivered at the *Materials Science and Technology in Engineering Conference* (MaSTEC 2021), 21-22 October, Hong Kong.

(P2) Yu, T. (2020). "High-performance seawater-mixed concrete", Invited Presentation, delivered at *the ACI Webinar Seawater-Mixed Concrete: A New Class of Sustainable Concrete*, 5-6 August, online.

(P3) Poon, C.S. (2020). "Hydration and strength development of cement pastes prepared by using seawater as mixing water", Keynote Speech, delivered at *the 3rd International RILEM Workshop on Concrete Durability and Service Life Planning (ConcreteLife 20),* 14-16 January, Haifa, Israel.

(P4) Yu, T. and Teng, J.G. (2024). "Seawater sea-sand concrete structures reinforced with fibre-reinforced polymer: innovative structural members and recent research advances", Plenary Keynote Presentation, delivered by Yu T at *the 9th Asia-Pacific Conference on FRP in Structures (APFIS 2024)*, 8-11 December, Adelaide, Australia.

(P5) Zhang P., Yu, T., Zheng, P.D. and Gao, Z.Y. (2023). “Key technical challenges in advanced FRP profile components”, Plenary Invited Presentation, delivered by Yu T at *the 12th National Conference on FRP for Construction*, 23-24 September, Changzhou, China.

(P6) Yu, T. (2023). “Novel marine structures based on fibre-reinforced polymer composites”, Invited Presentation, delivered at *the 3rd Conference on New Materials and Structures in Civil Engineering*, 1-3 December, Wuhan, China.

(P7) Yu, T. (2024). “Durability study on FRP-reinforced seawater sea-sand concrete structures”, Invited Presentation, delivered at *the 5th China International Congress on Composite Materials (CCCM-5)*, 25-28 July, Urumqi, China.

(P8) Yu, T. (2025). “FRP-reinforced seawater sea-sand concrete structures”, Invited Presentation, delivered at *the Towards Enhanced Structures and Sustainable Construction Workshop: FRP Solutions for Strengthening, Rehabilitation, and Internal Reinforcement*, 9-10 December, Sharjah, UAE.

(P9) Xia, Y. (2025), “Long-span Bridge Health Monitoring in Hong Kong - Past, Present and Future”, Keynote Speech, delivered at *the Sensing and Field Testing for Civil SHM: Experience, Challenges & Future Directions*, 8-9 September, Belfast, UK.

(P10) Cao, J.N. (2021), “Distributed Collaborative Edge Computing”, Keynote Speech, delivered at *the 2021 IEEE International Conference on Edge Computing (IEEE EDGE 2021)*, 18-20 December, Guangzhou, China.

7.3 Have any project team members taken leadership positions in editorial boards, scientific and professional organisations?

The project team has a strong record of leadership in editorial boards, scientific and professional organisations, as exemplified by the following.

(1) PC Yu is a Co-Editor-in-Chief of Journal *Advances in Structural Engineering*, an Associate Editor of ASCE *Journal of Composites for Construction*, and a member of editorial board of a few other journals; he is also the Senior Vice President of *the International Institute for FRP in Construction (IIFC),* the leading international institute in the field. Notably, PC Yu serves as the founding Chair of *the Technical Committee on SSC (TC-SSC) of Asian Concrete Federation (ACF)* since April 2024, leading the ongoing efforts in developing design guidelines and material specifications on SSC. PC Yu also serves as a member of the *ACI Committee 243 on Seawater Concrete*.

(2) Co-PI Poon is a past president of *Hong Kong Concrete Institute (HKCI)*. He has served on *the Advisory Council on the Environment (ACE), the Council for Sustainable Development*, and *the Advisory Committee for the Recycling Fund of the Hong Kong SAR Government*. He is an Editorial Board member of *Cement and Concrete Composites*, and an Editorial Advisory Board member of *Construction and Building Materials*.

(3) Co-PI Sun is a Fellow of *Royal Academy of Engineering (RAE)*, *Institute of Measurement and Control (IMC)* and *Institution of Engineering and Technology (IET)*.

(4) Co-PI Ni is a Member of Board of Directors of *International Association for Structural Control and Monitoring (IASCM)* and was the Vice President of *International Society for Structural Health Monitoring of Intelligent Infrastructure (ISHMII)* (2019 to 2021). He is a Co-Editor-in-Chief of *Journal of Infrastructure Intelligence and Resilience* and *Intelligent Transportation Infrastructure*, and an Academic/Associate Editor of three other journals.

(5) Co-PI Leung chairs the *RILEM Technical Committee on Optical Fiber Sensors for Civil Engineering Applications*. He has served as Associate Editor of many journals in his field, including *ASCE Journal of Materials in Civil Engineering*. Prof Leung is also the Chair of *the Hong Kong Accreditation Service Working Party on Construction Materials Testing*.

(6) Co-PI Dai is the Vice President of *ACF* and Committee Manager of *ISO/TC71 SC6* on “*Non-traditional Reinforcing Materials for Concrete Structures*”, and was previously the Vice President of *IIFC* and Technical Board Chair of *ACF*. He has served several international journals (e.g., *Journal of Composites for Construction*, *Composites Communications*, *Engineering Structures*)

as an Associate Editor, Guest Editor or Editorial Board Member.

7.4 Any documentary proof of the application of technologies arising directly from this project?

Yes. The team obtained documentary proofs for demonstration projects and the mock-up frame on FRP-SSC structures, and the establishment of a design guideline for the use of FRP in marine structures. The scanned copies are attached in Appendix 10.

7.5 Other awards and recognitions as a result of this project (please specify):

The following awards acknowledge work partially supported by, or connected to, this project.

PC Yu, *Distinguished Young Scholar Award in New Material Structures and New Structural Systems for Civil Engineering*, 2023. (A3 in Appendix 6)
Co-PI Dai, *Outstanding International Collaboration Award of JSCE*, 2022. (A4 in Appendix 6)
Co-I Xia, *Structural Health Monitoring Person of the Year Award*, 2025. (A5 in Appendix 6)

8. Impacts

8.1 What are the current and expected impacts of the project on the long-term development of Hong Kong (social or economic development, e.g. patent, technology transfer, collaboration with external organisations, etc.)?

This project, on the development of innovative FRP-SSC structures for sustainable marine infrastructure, is generating a foundational shift in the approach to marine infrastructure. Its outcomes are delivering immediate benefits while establishing a clear pathway for Hong Kong to achieve long-term economic and social benefits as well as technological leadership in sustainable construction. The impacts are multifaceted, as elaborated below.

Current Impacts on Hong Kong's Development
Intellectual Property Portfolio: The project has generated a portfolio of novel products such as ultrahigh-performance SSC (UHPSSC), FRP connectors, FRP-coated rebar, and hybrid FRP-concrete beams. This portfolio establishes a proprietary knowledge base within Hong Kong, creating opportunities for future licensing and commercialisation.

Technological Validation: The research has moved beyond the laboratory through demonstration projects that serve as critical proof-of-concept. These include FRP-SSC paving slabs for a local sewage plant, the reconstruction of a local pier and construction of a wave wall through collaboration with CEDD. These projects demonstrate the technology's viability for local contractors and government bodies. Furthermore, collaboration with CEDD on two additional projects has successfully integrated FRP bars into the city's development pipeline.

Design Guidance Documents: PC Yu and his team worked with CEDD to develop Hong Kong's first local Design Guidelines for FRP in Marine Structures. This is complemented by a Working Paper on FRP-coated rebars, a novel corrosion-resistant product developed in this project. These documents are pivotal for technology transfer, facilitating practical applications.

Expected Long-Term Impacts on Hong Kong's Development
Economic impact: FRP-SSC structures are expected to lead to life-cycle cost savings of 30-50% for marine infrastructure. This presents a compelling economic case for public and private investment. Over decades, this will translate into substantial conserved public funds for infrastructure maintenance and renewal. Crucially, the suite of matured technologies and Hong Kong's established experiences from pilot projects provide a strong foundation for exporting high-value engineering services to mainland China and other coastal nations/regions.

Environmental Sustainability and Social Benefit: FRP-SSC structures are expected to significantly reduce carbon emissions. When scaled across future marine projects, this will represent a significant decrease in the construction sector's carbon footprint. Socially, the deployment of longer-lasting, corrosion-resistant infrastructure means safer, more resilient piers, seawalls, and coastal facilities for the community, enhancing climate adaptation.

Global Leadership in Sustainable Marine Construction: Through active participation in international standards committees, such as ACI Committee 243 on Seawater Concrete and the Asian Concrete Federation's Technical Committee on SSC, chaired by Professor Yu, the team is systematically influencing global practices. This role ensures that Hong Kong is not merely an adopter but a primary shaper of international standards. Furthermore, the novel products and technologies, from UHPSSC and coated rebars to FRP connectors and hybrid beams, will establish Hong Kong as a global knowledge hub, positioning the city as a leading exporter of the novel products/technologies for next-generation marine infrastructure.

8.2 Others (please specify):

Nil

9. Sustainability of the Project

9.1 Whether there are new ideas evolved directly from this project?

Yes. There are a lot of new ideas evolved directly from this project, many of which have successfully attracted competitive research grants (e.g., Items 1-5 in Section 7.1).

9.2 Whether there are new projects evolved directly from this project?

Yes. Details are provided in Section 7.1.

9.3 Whether there are new collaborations developed directly from this project?

Yes. The team has developed collaboration with CEDD and Building Technology Research Institute (BTRi) of Hong Kong on field applications, design guideline development, and training of engineers. The team has also developed collaboration with several companies from the industry, including China Harbour Engineering Company, Anderson Concrete Limited, and Smart Construction Composite Materials Limited, on the construction of demonstration projects and batch production of the developed innovative structural materials/products.

9.4 Please give details on how much money and from which sources has been obtained/requested for the specific purpose of continuing the work started under this project.

The team has obtained many research grants to continue the work started under this project. Details are provided in Section 7.1.

10. Statistics on Research Outputs

	Peer-reviewed journal publications	Conference papers	Scholarly, books, monographs and chapters	Patents awarded/Filed	Other research outputs (please specify)	
					Type	No.
No. of outputs arising directly from this research project	215	26*	0	9		

*This includes conference presentations with an abstract but without a full paper, see Section 6.4.

11. Public Access of Completion Report

Please specify the information, if any, that cannot be provided for public access and give the reasons.

N.A.

12. The Layman's Summary

(describe in layman's language the abstracts and research impact of the project.)

Coastal cities like Hong Kong rely heavily on their coastal and marine (referred to as "marine" hereafter for brevity) infrastructure (e.g., ports, bridges & artificial islands) for social-economic development. This project addresses two critical challenges facing marine infrastructure: the deterioration of steel-reinforced concrete in corrosive marine environments and the increasing scarcity of freshwater and river sand for construction. The proposed innovative solution is to replace traditional materials with seawater sea-sand concrete (SSC) reinforced with corrosion-resistant fibre-reinforced polymer (FRP) composites, thereby creating durable and sustainable FRP-SSC structures.

Through six years of interdisciplinary research, the project has established the scientific and engineering foundation for this new paradigm. It successfully elucidated the hydration mechanisms of SSC and developed novel material products like ultra-high-performance SSC (UHPSSC) along with advanced hybrid FRP rebars, grid tubes and connectors. Beyond materials, the project engineered innovative structural forms, including hybrid FRP-concrete beams/columns and beam-column connections, optimized for superior mechanical performance. Furthermore, it integrated smart monitoring capabilities through embeddable sensors and a solar-powered IoT platform, enabling real-time structural health assessment. To ensure long-term reliability, the team conducted comprehensive durability tests and developed sophisticated multi-scale, multi-physics predictive models capable of forecasting the performance of FRP-SSC structures over their entire life cycle.

Critically, this research has moved beyond the laboratory through demonstration projects that serve as essential proof-of-concept. In collaboration with the Civil Engineering and Development Department (CEDD) of Hong Kong SAR, the technologies have been applied in the reconstruction of a local pier and the construction of a wave wall, demonstrating the technology's viability for local contractors and government bodies.

This project is generating a foundational shift in the approach to marine infrastructure, with profound and multi-scale impacts. FRP-SSC structures are projected to offer significant life-cycle cost savings and a significant reduction in carbon emissions, directly supporting Hong Kong's carbon neutrality goals while delivering safer, more resilient coastal facilities. Moreover, the comprehensive suite of outputs, including the novel material portfolio, hybrid structural designs, predictive models, and design methods, positions Hong Kong at the forefront of sustainable marine construction. This establishes the city not only as the originator of this innovative paradigm but also as a future hub for exporting high-value engineering services, technologies, and cutting-edge knowledge for next-generation sustainable marine infrastructure worldwide.