CONSTRUCTION
INDUSTRY COUNCIL
建造業議會

SPECIAL ISSUE

CIC
INNOVATION
AWARD
建造業議會創新獎

INNOVATION IN CONSTRUCTION

RESEARCH JOURNAL 2016

ISSN 2312-8291

Creating Impacts Through Innovation

Innovation In Construction
This Journal is available online, please visit: www.cic.hk

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Printed in Hong Kong.

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About Construction Industry Council

The Construction Industry Council (CIC) was formed on 1 February 2007. CIC consists of a chairman and 24 members representing various sectors of the industry including employers, professionals, academics, contractors, workers, independent persons and Government officials.

The main functions of CIC are to forge consensus on long-term strategic issues, convey the industry's needs and aspirations to the Government, as well as provide a communication channel for the Government to solicit advice on all construction-related matters. In order to propagate improvements across the entire industry, CIC is empowered to formulate codes of conduct, administer registration and rating schemes, steer forward research and manpower development, facilitate adoption of construction standards, promote good practices and compile performance indicators.

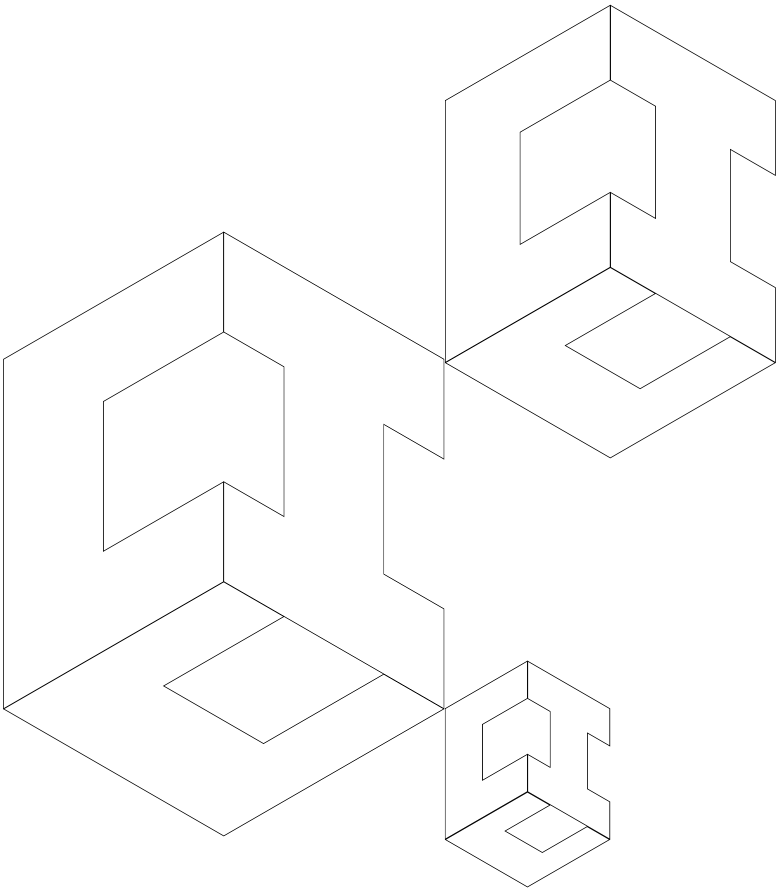
CIC has set up Committees to pursue initiatives that will be conducive to the long-term development of the construction industry. Further information is available on www.cic.hk.

VISION

To drive for unity and excellence of the construction industry of Hong Kong.

MISSION

To strengthen the sustainability of the construction industry in Hong Kong by providing a communications platform, striving for continuous improvement, increasing awareness of health and safety, as well as improving skills development.



CHAIRMAN's MESSAGE

I am pleased to announce the publication of this special issue of our Research Journal "*Innovation in Construction*" (*iCON*). With a focus on the inaugural CIC Innovation Award 2015 ("Award"), this issue continues to act as a communication platform between industry stakeholders and researchers to exchange innovative knowledge and ideas, thereby enhancing the overall performance of the industry.

Embracing the Construction Industry Council (CIC)'s vision to drive for excellence of the industry, the Award is a significant occasion for local and worldwide industry practitioners and academia to showcase their innovative creations in the categories of construction materials, technology and management. It also highlights Hong Kong's achievements in promoting research, innovation and development in the construction industry to our international audience.

CIC promotes innovation as the key to the efficient and sustainable development of the construction industry. In celebration of excellence and recognition of the outstanding works, the Award motivates our stakeholders to adopt innovation and provides a high-profile platform to realise their aspiration to become leaders in the field. CIC will spare no effort in promulgating these ideas and creating opportunities for the project teams.

This new issue of *iCON* records the awardees' inventions which were selected among a significant number of exceptional works. We are delighted to see the active engagement and participation of the industry stakeholders in the Award, reflecting our strong passion for innovations and our determination to strive for the best. Indeed, it is the support of all that lays a solid foundation to produce high-quality works.

The Award would not have been a success without the tremendous efforts of the prestigious Judging Panel who are all leading construction professionals with different expertise. They have exercised professional judgment during the rigorous assessment process to make a strenuous decision in selecting the winners. I would like to extend my heartfelt gratitude to all the local and overseas judges, particularly Ir Kevin POOLE and Prof. Christopher LEUNG, who are the Chairman and Vice-chairman of the Organising Committee of the Award.

May I also take this opportunity to thank all participants for their invaluable contributions, congratulate the awardees for their accomplishments, and wish all pioneers every success.

Sr CHAN Ka-kui
Chairman
Construction Industry Council

EDITORIAL

It is our honour to chair the Organising Committee of the CIC Innovation Award, the flagship event of the local construction industry in 2015 co-organised by the Committee of Environment, Innovation and Technology (Com-EIT), and Committee of Productivity and Research (Com-PNR) of the CIC. This special issue of "*Innovation in Construction*" (*iCON*) captures the essence of this event, demonstrating the industry's efforts in promoting innovations and technology in Hong Kong.

In the process of choosing the best out of the best, the Judging Panel had studied each of the submissions meticulously and assessed them based on their innovation and originality, impact, and applicability. Not only are all the winning projects featured in the following pages pioneering in their own area, they have also demonstrated their functional significance on the site-, project-, industry-, and city-level respectively.

The groundbreaking invention of Bendable Concrete by Prof. Victor LI from the University of Michigan has stood out from the diverse collection of international proposals, while the down-to-earth Anti-Heat Stress Clothing for Construction Workers developed by Prof. Albert CHAN and his cross-disciplinary research team has made to the top of local contenders. Four other awarded projects by Gammon Construction Limited, Ove Arup and Partners Hong Kong Limited and Sino Green in Hong Kong Limited, The Chinese University of Hong Kong, and The Hong Kong Polytechnic University, are expected to help transform the way we build in a more productive, safer, and greener manner. Another highlight of the Award is the special category for young innovators who are below the age of forty. We are particularly impressed by the efforts and dedication to improve the construction industry by Ir Dr. Carlos LAM from the Civil and Engineering Development Department, and Ms. Yuhan NIU together with her research team from The University of Hong Kong.

It is heartening to see these innovative solutions being documented in this new issue of *iCON*. Our congratulations go to all awardees for their commendable achievements. We also have to offer our sincere thanks and appreciation to other Members of the Judging Panel and the Organising Committee for their contributions in making this meaningful event a success.

With a view to striving for continuous improvement of the industry, we will go on to support research efforts to deliver more innovative and practical creations. We look forward to witnessing the rippling effects of these successful ideas and the birth of more innovations.

Ir Kevin POOLE
Chairman
Organising Committee

Prof. LEUNG Kin-ying, Christopher
Vice-Chairman
Organising Committee

CIC INNOVATION AWARD 2015

Innovation is the key to the efficient and sustainable development of the construction industry. The CIC thus encourages innovation in construction to cultivate new ideas. The CIC Innovation Award (Award) aims to spearhead development of new concepts to enable continuous enhancements in the construction industry of Hong Kong. It also aims to recognise new technologies and scientific breakthroughs by academia and industry practitioners, as well as to arouse international awareness on achievements in research and innovation in the construction industry of Hong Kong SAR, the Mainland China and overseas.

The Award was open to innovative ideas that focus in one of the following scopes:

Construction Materials	New construction materials beneficial to the built environment or conventional construction materials which are more sustainable
Construction Technology	Procedures and techniques such as prefabrication, automation, robotics, etc in construction which can be applied to different projects
Construction Management	Management tools and applications that enhance safety, environmental protection, project management and productivity in construction

Since its launch in April 2015, the Award had received overwhelming support not only from the local construction industry, but also overseas practitioners and academics. Following a series of assessment by the Judging Panel, 8 awards were announced at the Award Presentation Ceremony in December 2015. More details are available on http://cicinnovationaward2015.hkcic.org/.

CIC Innovation Award Presentation Ceremony, the Government House

JUDGING PANEL

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Ir Kevin POOLE
Executive Director
Third Runway
Airport Authority Hong Kong

Panel Vice-Chair

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Civil and Environmental Engineering Department, The Hong Kong University of Science and Technology

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A. James Clark Chair Professor
Department of Civil & Environmental Engineering, University of Maryland, USA

INTERNATIONAL GRAND PRIZE

Bendable Concrete

Left:
Prof. Victor LI
University of Michigan

Right:
The Honourable C.Y. LEUNG
Chief Executive, HKSAR

Bendable Concrete

Victor C. LI[1,*]

[1] University of Michigan, USA

Concrete is arguably the most important construction material. Since its early days, concrete has always been known as a material strong in compression, but tends to be brittle in tension. While the use of steel reinforcement has made concrete highly effective in large-scale constructed facilities, improvement in resiliency, durability, and sustainability of infrastructure can be further enhanced if concrete can be made ductile. Engineered Cementitious Composites (ECC, also known as Bendable Concrete) has been designed to overcome the brittleness of concrete. With a tensile ductility of 2-5% and a self-controlled tight crack width less than 100 µm, ECC enables high damage tolerance of structural members even under fully reversed shear loading and impact loading, and demonstrated unusual durability under a variety of environmental exposures. This article summarises some key properties of ECC and highlights selective recent applications in full-scale infrastructure.

Keywords: concrete, innovation, ductile, ECC, infrastructure.

1. THE NEED FOR INNOVATION IN CONCRETE TECHNOLOGY

Since the introduction of concrete in the 1800's, it has become a ubiquitous material for almost all imaginable constructed facilities. These include transportation systems such as highway and airfield pavements, and shipping ports, building systems from single-family homes to the tallest buildings in the world, water systems from small irrigation channels to large dams, and energy systems from nuclear power containment buildings and cooling tower to ultra tall wind turbine towers. The impact of concrete as a construction material on our quality of life and on modern commerce has never been greater. Concrete is arguably the most important man-made engineering materials. It occupies the top position in terms of consumption amount amongst all engineering materials, at 12 billion tonnes or 2 tonnes per person on an annual basis.

Concrete technology has advanced in many significant ways over the last fifty years. The discovery of lowering porosity through the use of low water/cement ratio and the addition of microsilica led to the development of high strength concrete in the 1970-90's. This trend was aided by the availability of high range water reducing agents – chemical additives that maintain good workability despite reduced water content in the concrete mix. More recently, it is recognised that high strength alone is not adequate to maintain the performance of concrete over its lifetime. Various efforts during 1990-2010 led to High Performance Concrete that embraced a broader definition of quality beyond strength, including durability by denser particle packing, and higher consistency in the quality of cast concrete by self-consolidation without depending on skilled manual vibration. In the last decade, there has been increasing focus on greening concrete through various processes, including the adoption of industrial waste streams into concrete mixes, and through recycling of used concrete as artificial aggregates. The reduction of energy requirement and carbon emission in the production of cement via improved cement kiln technology has also contributed to greening concrete. In summary, the advances in concrete with higher compressive strength, enhanced quality and durability, and reduced environmental impacts, have led to a variety of improvements in concrete infrastructure and the concrete industry.

Despite technological advances as highlighted above, today's concrete infrastructure continues to suffer from required repeated maintenance, and a lack of resiliency requires costly repair and even causes loss of human life after a major loading event. Cases in point are:

- Many countries including the US, Canada, Germany, Japan and Korea have annual expenditure outlays on infrastructure repair outstripping expenditures on new construction.
- Recent events such as 2005 US Katrina Hurricane, 2011 Japan Tohoku earthquake, and 2013 Philippine Typhoon Haiyan point to the susceptibility of infrastructure to natural forces.

In addition, there is increasing awareness that the built environment dominated by concrete infrastructure is often at odds with the natural environment in terms of life cycle energy and carbon footprints. Innovations are urgently needed to address these grand challenges that are adversely affecting the quality of life of urban communities.

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[*] vcli@umich.edu | Prof. Victor LI

The underpinning shortcoming of normal concrete is poor tensile load carrying capacity. Specifically, concrete has a fracture toughness less than 0.1% of that of steel. The propensity to cracking has significant implications on durability of concrete infrastructures under normal service conditions and on safety of infrastructures under severe loading. The brittle nature of concrete has never been successfully addressed in the past.

2. WHAT MAKES ECC UNIQUE?

Imagine a new concrete that has low embodied energy and has a negative carbon footprint, durable under a broad range of exposure environments and even repairs itself when damaged. Imagine that this concrete is also tolerant to damage thus minimising both infrastructure repair cost and recovery time after a major loading event. While such a concrete does not exist today, Engineered Cementitious Composites (ECC), also known as Bendable Concrete, has been designed to support civil infrastructure that are durable, resilient and sustainable.

ECC is a family of ductile concrete with a compressive strength ranging from 50 MPa to 200 MPa. The unique feature, however, is its tensile ductility, about 3-5% in tensile strain capacity as measured by direct tension in a loading machine and recorded by Linear Variable Differential Transformers (LVDTs) (Li, 2003). This is about 300 to 500 times the tensile strain capacity of normal concrete and fiber reinforced concrete (about 0.01%). Figure 1 shows a tensile stress-strain curve of ECC under direct uniaxial tension test. ECC can be designed for a variety of functionalities, including self-consolidating (Kong *et al.*, 2003), self-sensing (Lin *et al.*, 2011), self-thermally adapting (Desai *et al.*, 2014), and self-healing (Herbert and Li, 2013).

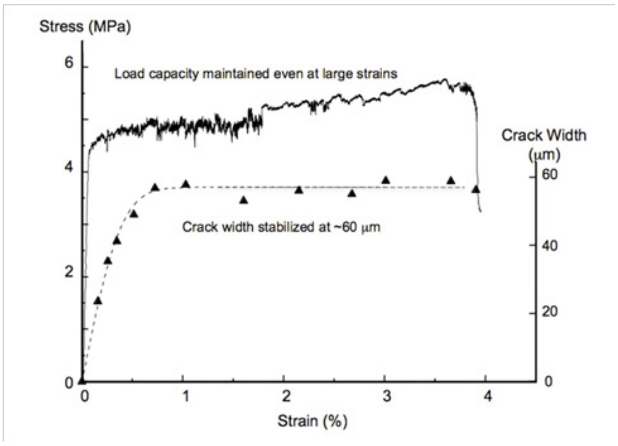


Figure 1 ECC has tensile ductility several hundred times that of normal concrete, and crack width self-controlled to less than 100 100 μm.

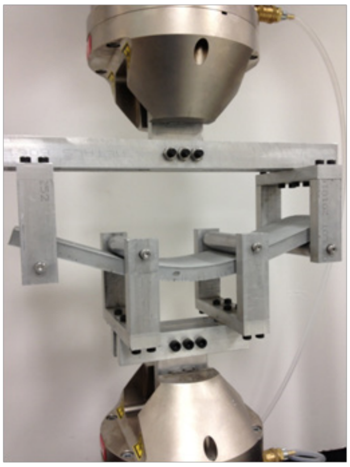


Figure 2 ECC flexes without brittle fracture

Most high strength concrete fails at a tensile strain of 0.01% to 0.2%, despite its high compressive strength. Textile concrete can have high tensile ductility. However, they are limited to certain types of precast applications. ECC has emerged as the most ductile concrete in full-scale cast-in-place applications. Figure 2 shows a slab of ECC under flexural load. The large deformability without succumbing to brittle fracture is evident.

The ductility of ECC also makes the material highly tolerant to impact loading. Substantially higher impact load resistance and energy absorption have been demonstrated (Maalej *et al.*, 2005; Yang and Li, 2012). Figure 3 shows the contrast of response between a ECC slab and a common concrete reinforced with steel, when both are subjected to impact loading in a drop weight tower test.

Unlike high strength concrete, ECC has a design basis (Li, 1993) that does not aim at eliminating flaws, but rather controlling the size distribution of flaws so that controlled microcracking is allowed. These microcracks with tight crack width, typically less than 100 μm, contribute to the tensile ductility when overloaded, then subsequently undergo self-healing (Yang *et al.*, 2011). The self-healing mechanism is an accelerated form of continued hydration and pozzolanic reaction. This damage management paradigm (as opposed to damage prevention) is akin to that of nature's nacre - the iridescent material on the inside of abalone shells. Similar to cement, nacre is made of brittle calcium carbonate platelets that slip over one another under load. The ductile deformation then undergoes self-healing to protect the soft-body of the abalone. In many ways, and particularly the deliberate introduction of a large amount of slip surfaces through microfibers with controlled bonding, ECC emulates the amazing features of nature's nacre.

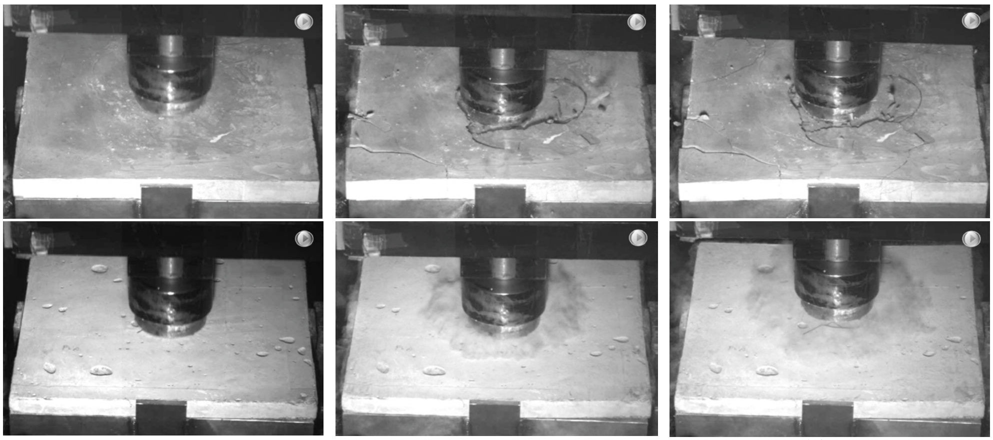
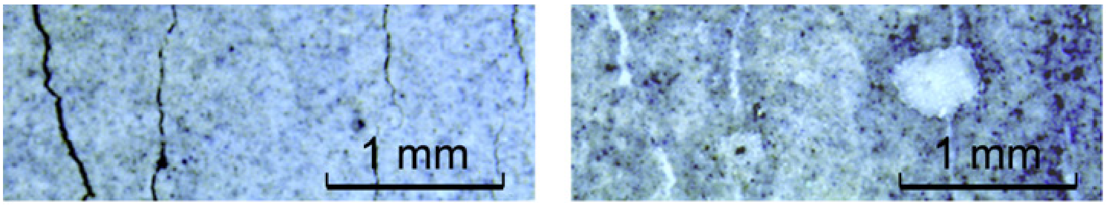


Figure 3 Impact response of reinforced concrete (top row) and ECC (bottom row). The time series (left to right) shows just before impact, at impact, and after rebound of impact tub on slab.



(a) (b)

Figure 4 ECC self-heals crack damage when exposed to water and air. (a) before and (b) after healing

(a) (b)

Figure 5 (a) Spalled mortar specimen after 95 hours accelerated corrosion, and (b) ECC specimen after 350 hours accelerated corrosion.

ECC undergoes self-healing of crack damage requiring only the presence of air and water. Figure 4 shows an ECC specimen before and after healing.

The intrinsically tight crack width without depending on steel reinforcement contributes to enhanced durability of infrastructure even under an aggressive environment. For example, it has been shown that under chloride environment, the effective chloride diffusion coefficient of ECC remains substantially lower than that of normal concrete under the same load and chloride exposure (Sahmaran *et al.*, 2007). The rate of corrosion of the reinforcing steel is also significantly lower under salt spraying and drying cycles (Miyazato and Hiraishi, 2005). Further in an accelerated corrosion test using an impressed current on the re-bar, cover spalling in ECC is fully suppressed (Sahmaran *et al.*, 2008) (Figure 5).

Designing a ductile concrete by trial-and-error is next to impossible due to the infinite combination of fiber (type, length, diameter), matrix (toughness, flaw size and distribution) and interface (chemical and frictional bonds) parameters. A strong theoretical foundation had to be developed to guide the composite development process. Meeting this challenge led to the first ever micromechanical model of strain-hardening ductile concrete (Li and Leung, 1992; Li, 1993).

The second challenge was measurements of micromechanical parameters, including fiber/matrix interaction properties. New experimental methods in microfiber pullout test (Li *et al.*, 1990; Katz and Li, 1992) had to be developed, and a number of hither-to unknown micromechanisms were identified, including slip-hardening processes and snubbing mechanisms of synthetic fibers as they debond and slide out of the matrix during matrix crack propagation.

The development of the theoretical design basis of ECC combined with experimental techniques to quantify micromechanical parameters was critical in the successful realisation of ductile ECC. Research on ECC requires background in concrete technology, material science, and mechanics of materials. Interdisciplinary research inspired by nature's nacre led to today's ECC technology.

3. BENEFITS AND IMPACTS TO THE CONSTRUCTION INDUSTRY

Over the last decade, ECC has emerged in full-scale civil infrastructures in the transportation, building, water and energy industry domains. ECC has been applied cast-in-place, as well as in precast structural elements. In cast-in-place applications, ECC with self-consolidation fresh property has been used. Both new structures and repair/retrofitted structures have benefited from the unique properties of ECC.

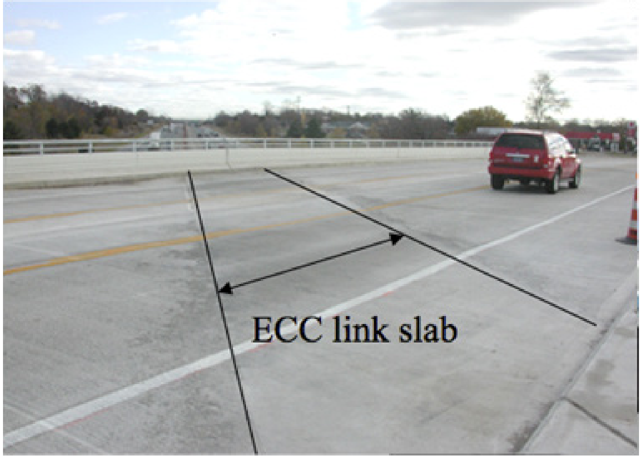
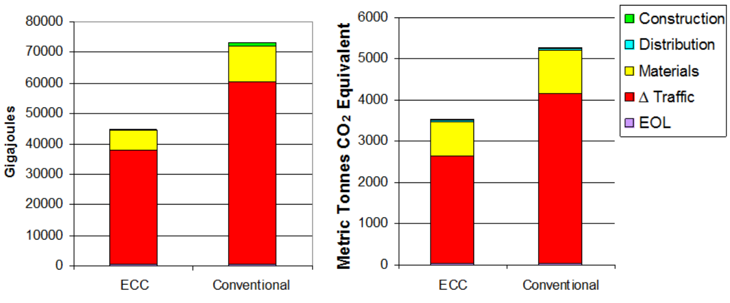


Figure 6 ECC link slab replaces conventional expansion joints to enhance the service life of bridge deck in the US.

Figure 6 shows a bridge deck with an ECC link slab (Lepech and Li, 2009) replacing a conventional expansion joint that typically requires frequent repairs. This application takes advantage of the large deformability of ECC to act like an expansion joint when the deck needs to lengthen and shorten due to temperature induced expansion and contraction. The computed tensile strain demand on this link slab was over 2%, a value no normal concrete, high strength or not, can withstand without brittle fracture. The ECC was batched in a ready-mix plant and transported to site by ready-mix trucks. Six truck loads of self-consolidating ECC (Figure 7) were deployed in this retrofit application. After ten years in use, this link-slab remains in a condition similar to when it was first installed, thus demonstrating its durability under traffic and severe weather conditions (freeze-thaw cycles in winter) in the state of Michigan.

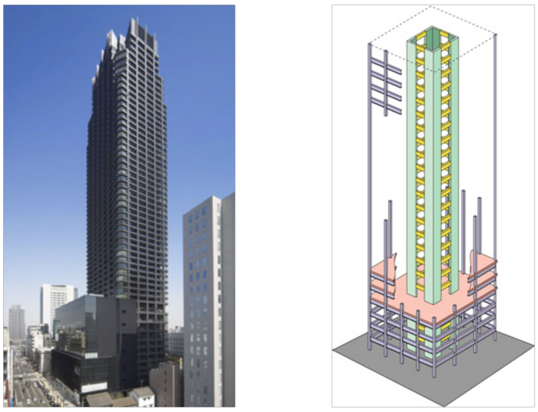
Figure 7 Self-consolidating ECC enhances quality control in cast on-site projects

The ECC link slab provides an opportunity to study infrastructure sustainability when advanced construction material is introduced. Keoleian *et al.* (2005) conducted a comparative life-cycle analysis of resource input and pollutant emissions between a bridge deck that utilises ECC link slab and a bridge deck with conventional expansion joints. They found that about 40% of total primary energy and carbon dioxide equivalent were saved due to the reduced maintenance frequency requirement and the associated impact on traffic patterns when ECC link-slab is used to replace conventional expansion joints (Figure 8). Simultaneously, the life cycle cost of the 60 years service life was found to be reduced by 37%.



(a) **(b)**

Figure 8 Life cycle (a) primary energy consumption and (b) CO2 equivalent for the ECC shows about 40% less than that of conventional bridge deck systems.



(a) (b)

Figure 9 ECC coupling beams were used to enhance seismic safety in the tallest R/C building in Japan. (a) the 60 story Kitahama Building in Osaka, Japan, and (b) schematic showing four coupling beams (in yellow) on each floor levelcorrosion.

Figure 10 ECC coupling beams as seen during building construction

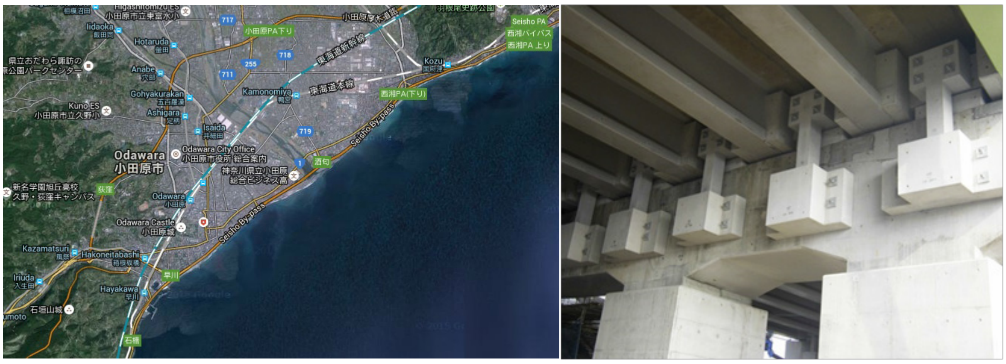


Figure 11 ECC dampers were used to enhance seismic safety and durability of the Seisho By-Pass Viaduct located on the coastline in Japan.

Figure 9(a) shows the use of ECC in the tallest reinforced concrete (R/C) building in Japan - The 60-story Kitahama Building in Osaka, Japan. In this application, the ECC coupling beams serve to absorb energy during an earthquake (Kanda *et al.*, 2011). The high tensile ductility of ECC enables a desirable hysteresis behaviour of the coupling beams under reversed shear loading. Extensive experiments demonstrated the damage tolerant response with load capacity remaining stable even at high drift angles. The coupling beams were precast in a precast yard, transported to the construction site, and dropped into location four pieces on each floor level, connecting to the core wall (Figure 9(b)). Figure 10 shows the coupling beams while the building was under construction.

ECC dampers were adopted to retrofit the Seisho By-Pass viaduct in Japan, to enhance its seismic safety. Over one thousand dampers were precast and installed. The viaduct retrofit dampers were designed to absorb energy during seismic loading, and remain durable in an aggressive chloride and water environment (Figure 11). In this application, both tensile ductility and tight crack width of ECC are critical to the performance of the retrofitted viaduct.

The field applications of ECC briefly highlighted above are motivated by the needs to reduce maintenance (as in bridge deck with ECC link slab), and to enhance safety under natural hazards (as for tall buildings with ECC coupling beams). In the case of the ECC dampers, both attributes become important and must be embodied in a single concrete. Two concrete materials, one ductile and the other durable, would not be effective. These applications are illustrative of the wide applicability of the new ductile concrete.

4. CONCLUSIONS

ECC represents a paradigm shift from damage prevention to damage control and management in concrete design. Instead of tight packing of ingredients as in high strength concrete, ECC emphasises synergistic load sharing among the composite components under overloading. The result is a new concrete with high tensile ductility, bendable under flexural load.

The invention of ECC enables structural engineers to provide a safer, more durable, and sustainable built environment for society. Safety can be greatly improved with ECC because it is damage tolerant when subjected to large loads such as earthquakes and impacts (e.g. blast loading). ECC improves durability through self-control of cracking that typically leads to deterioration of concrete and its reinforcement. Self-healing of ECC further aids in managing crack damage. Life cycle assessment modeling results confirmed that the adoption of ECC technology leads to a reduction of carbon and energy footprints of constructed facilities. ECC can contribute to the construction industry's ongoing worldwide efforts towards more sustainable and resilient infrastructure. In short, ECC represents an enabling technological innovation for enhancing harmony between the built and natural environment.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the contributions to ECC development by former and current graduate students whom he has the privilege to work with, and the E.B. Wylie Collegiate Professorship at the University of Michigan.

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BIOGRAPHY

Prof. Victor LI is the E.B. Wylie Collegiate Professor of Civil and Environmental Engineering at the University of Michigan, Ann Arbor. His research interest is in multifunctional concrete materials targeted at enhancing infrastructure sustainability and resiliency. He led the research team that invented Engineering Cementitious Composites, popularly known as "Bendable Concrete". Prof. LI was named a Thousand Talent Specialist in China in 2013. He received the Distinguished Graduate Mentor Award in 2015 and the Distinguished Faculty Award in 2006 from the University of Michigan. In 2005, he received the Stephen S. Attwood award bestowed by the College of Engineering at the University of Michigan. In 2004, Prof. LI was honored by the Technical University of Denmark with a "Doctor technics honoris causa" in recognition of his "outstanding, innovative contributions to materials research and engineering and providing our society and the construction industry with new, safe and sustainable building materials". Prof. LI is a Fellow of the American Society of Civil Engineers, the American Society of Mechanical Engineers, the World Innovation Forum, and the American Concrete Institute. His research and societal impacts have been featured in the CBS Evening News, the Discovery Channel, the Architectural Record, the American Ceramic Society, the Portland Cement Association, and the Forbes Magazine, amongst many other public media. Prof. LI is named inventor on ten US patents.

LOCAL GRAND PRIZE

Anti-Heat Stress Clothing for Construction Workers in Hot and Humid Weather

Left:
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Chief Executive, HKSAR

Right:
Prof. Albert CHAN
The Hong Kong Polytechnic University

ANTI-HEAT STRESS CLOTHING FOR CONSTRUCTION WORKERS IN HOT AND HUMID WEATHER

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Summer in Hong Kong is hot and humid. With prolonged exposure to direct sunlight, construction workers who need to undertake physically demanding work are vulnerable to heat stress. Although construction workers are recommended to wear thin, light, and breathable clothing while working in hot weather, specific guidelines that enable practitioners to wear appropriate summer work uniform remain lacking. Solid evidence regarding the benefits of wearing such uniforms is also scant. To bridge these gaps, this research aimed to develop an anti-heat stress uniform to protect workers from extreme heat and high humidity. Fabric selection, clothing design, and performance assessment were employed through a scientific approach. The uniform was designed and produced with superior heat-moisture performance of fabrics, smart design and industry specific requirements in mind. With higher one-way transferability and liquid moisture management capacity, the new generation of moisture-management textiles improves fabric breathability, speeds up sweat evaporation and helps to reduce heat stress. Validity tests were conducted on the properties of the newly designed uniform inside a climatic chamber. The results showed a remarkable reduction of physiological strain by 16.7% and body heat storage by 28.8% over conventional work-wear, with wearers having lower core and skin temperatures and better physiological strain indices. The field studies were administered to evaluate the acceptability of the new uniform. The findings indicated that over 87% of the workers preferred to wear the anti-heat stress uniform that kept them cool, dry, and comfortable without impeding work performance. The well-being of construction workers with the new uniform is enhanced because the uniform exhibits excellent capacity in alleviating body heat strain and improving wearing comfort. The design of the new uniform may contribute to delivering an industry standard of heat stress controlling measure that has been adopted by the Construction Industry Council.

Keywords: thermal-moisture performance, smart design, human wear trial, climatic chamber, field survey.

1. INTRODUCTION

Summer in Hong Kong is hot and humid, which is attributed by subtropical climate and high urbanisation. Construction workers are susceptible to heat stress because they commonly perform physically demanding tasks under direct sunlight for a prolonged period (Chan *et al.*, 2012). The government and the industry have taken initiatives to lay down a series of precautionary guidelines and fundamental practice notes to safeguard workers laboring in hot weather. However, it is disturbing that high frequency of verifiable heat-related incidents continued to plague the local construction industry (Chan *et al.*, 2013).

The alarming heat-related incidents in the Hong Kong construction industry have raised overwhelming concern and compelled government agencies, industy stakeholders, and academia to develop and implement appropriate precautionary measures that can protect workers against heat stress. Although construction workers are recommended to wear thin, light, and breathable clothes while working in hot weather (Construction Industry Council, 2013; Labor Department, 2014), precise criteria for "appropriate" summer work clothes are lacking. Moreover, inappropriate dress behavior and insufficient personal protection were also observed on-site, such as semi-nude behavior, which may pose a high risk of skin cancer because of direct exposure to solar ultraviolet radiation (Chan *et al.*, 2013). Construction workers usually wet their clothes by sweat when they perform physically demanding work during summer time in Hong Kong. Properly designed construction work clothes do not get wet easily and protect wearers from UV sunrays and possible skin cancer.

Heat-related illnesses, inadequate heat stress controlling measures, and inappropriate dress behavior in the Hong

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Kong construction industry call for the engineering and promotion of proper summer work uniform for construction workers. In this regard, designing and engineering the Anti-Heat Stress Clothing (AHSC) for construction workers, which consider both scientific rigour and practical problem solving, is urgently needed. Such clothing is expected to deliver a scientifically rigorous standard of heat stress controlling measure that is valid and practical to implement in the Hong Kong construction industry.

The present study attempts to bridge these gaps by designing and evaluating the AHSC that is suitable for working in hot and humid weather. The paper starts by outlining the research background. A scientific approach that incorporates fabric selection and computer simulation, clothing design, and performance assessment is addressed. Results are subsequently reported and discussed. The paper concludes by highlighting how the newly designed work uniform contributes to promoting the well-being of construction workers as well as to delivering an industry standard in the construction industry.

2. MATERIALS, METHODS, AND CALCULATIONS

The primary objectives of this study were set out to: 1) design and engineer clothing for construction workers which is appropriate for extreme physiological conditions in hot and humid weather; and 2) evaluate the effectiveness of the newly designed clothing for construction workers. The nature of the present research called for a multidisciplinary team that possesses expertise and experience in occupational safety and health, materials science, textile science, and biological and exercise science. To fulfill the research objectives, fabric selection, clothing design, and performance assessment[1] were incorporated in this multidisciplinary study (Figure 1). The multidisciplinary research team contributed to managing the various theoretical, scientific, technical, statistical, socio-political, and practical facets as well as in producing an integrated picture of research context.

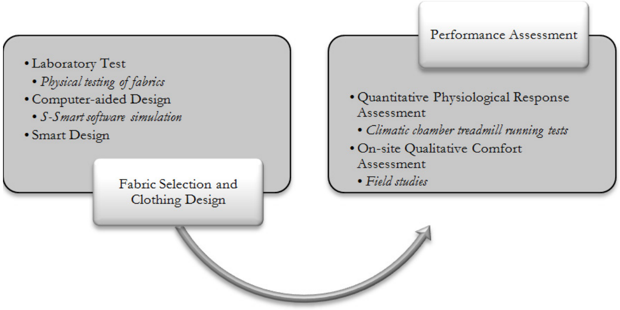

Figure 1 Research methods

2.1 Physical testing of fabrics

A series of objective measurements have been undertaken to identify the basic thermal-moisture and mechanical properties of thirty-seven commercially available fabrics (12 for T-shirt, 18 for trousers, and 7 for reflective strip). All the fabrics were washed according to the washing procedure of AATCC 61 (2006) and stored in an air-conditioned room at 21 °C and 65 relative humidity (ASTM D1776, 2004) for at least 24 hours to reach equilibrium regain before conducting the objective measurements in an environment of 23°C and 60% relative humidity. Thermal conductivity λ ($\mathrm{W/m^2}$ °C) is a property of fabric that expresses the heat flux that will flow through the material if a certain temperature gradient exists over the fabric Equation (1).

$$\lambda = \frac{W \times D}{A * \Delta\, T} \qquad (1)$$

where W is heat flux (W) measured by Thermolabo II KES-F device, D is thickness of fabric (m), A is specimen surface area (25×10^{-4} $\mathrm{m^2}$), ΔT is temperature gradient (10°C).

The air resistance (KPa•s/m) of the specimens was measured using KES-F8-AP1 (Kato Tech Co. Ltd., Japan) tester (ASTM D 737-96, 2003). A smaller value of it indicates better air permeability of the fabric and vice versa.

The water vapour transmission rate of the specimens was tested according to the international standard (ASTM E96, 2005). The inverted cup test was conducted, during which the measuring cup was weighted at 12, 24, 36, 72 h after placement in the air-conditioned room at an environment of 23°C and 60% relative humidity. The water vapour permeability of the fabric was calculated from Equation (2).

$$WVTR = \frac{\Delta G}{t * A} \qquad (2)$$

where WVTR is the rate of water vapour transmission ($\mathrm{g/m^2/day}$), ΔG is the weight change (g), t is time interval between the two measurements (h), A is test area ($\mathrm{m^2}$).

Overall moisture management capacity of the fabrics was measured by a moisture management tester (Hu *et al.*, 2005) according to AATCC 195 (2012). This instrument was used to test the liquid water transfer and distribution properties of the fabrics. The indices of overall moisture management capacity (OMMC) values are graded and interpreted as: Grade 1: 0-0.2, poor; Grade 2: 0.2-0.4, fair; Grade 3: 0.4-0.6, good; Grade 4: 0.6–0.8, very good, and Grade 5: > 0.8, excellent (Hu *et al.*, 2005).

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[1] The research methods have been elaborated in the published papers: Chan *et al.* (2015a, 2015b, 2016).

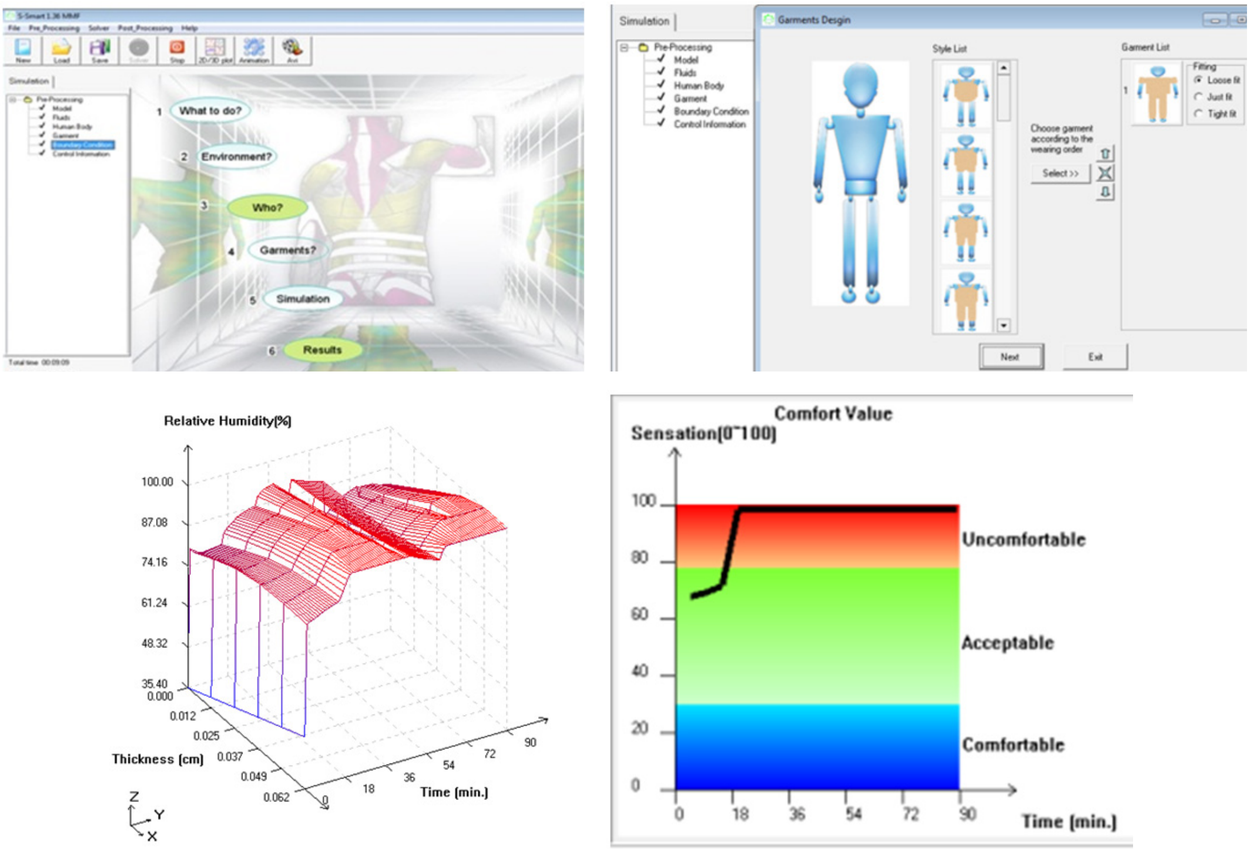

Figure 2 S-smart system for predicting fabric thermal-moisture performance

Contact angle of the fabrics was taken by using a contact angle meter model CAM-Micro (Tantec Inc. Denmark). The measurements were taken on both sides of the sample. The fabric can be hydrophilic when contact angle is smaller than 90°, whereas it is hydrophobic when contact angel is larger than 90°.

The ultraviolet protection factor (UPF) is measured in accordance with AS/NZS 4399 (1996). The UPF can be categorised as: range 15-24, good protection; range 25-39, very good protection; and range 40-50, 50+, excellent protection (AS/NZS 4399, 1996).

2.2 S-Smart software simulation

In the S-smart system, the thermal physiological status of the human body can be simulated based on the external environment, characteristics and activities of the human body, and the coupled heat and moisture transfer processes in the clothing and external environment (Guo *et al.*, 2013). The S-smart system provides a platform consisting of three modules: (i) pre-processing, (ii) simulation, and (iii) post-processing (Figure 2). In the pre-processing stage, the boundary conditions of the human-clothing-environment system are identified and regulated according to the fabric's physical properties and the practical situation in which the clothing is used (i.e., previous field studies at construction sites, Chan *et al.*, 2012). These boundary conditions include physical activities, meteorological parameters, and demography of the wearers. The computational simulation is executed by regulating the information on clothing, body thermoregulation, and boundary conditions and the control information in the pre-processing stage. The parameters are then transferred into the related mathematical models and are run according to the computational scheme (Guo *et al.*, 2008; Mao *et al.*, 2011). The simulation results for the human physiological responses, including body core temperature, mean skin temperature, and microclimate humidity, are provided in the post-processing stage.

2.3 Smart design

The uniform was designed and produced in consideration of heat-moisture performance of fabrics, smart design, and industry specific requirements. The Hong Kong construction workers usually perform outdoor works under hot and humid conditions in summer; thus, thermal comfort, which involves heat and moisture regulation in the human body, is regarded as a key performance indicator in new uniform design (Chan *et al.*, 2015a). Evaporation is the major avenue to dissipate the heat in a hot environment (Havenith, 1999). During summer in Hong Kong, construction workers may be difficult to dissipate heat via evaporation because high humidity inhibits sweat efficiency (Epstein *et al.*, 1986). The major requirement of the newly designed uniform is to facilitate sweat evaporation, which largely relies on the improvement of air ventilation and liquid/vapour moisture transfer. In addition to the physical properties of fabrics, the clothing design is closely related to the thermal and moisture performance of clothing (Nielsen *et al.*, 1989). For instance, previous studies have demonstrated that the use of meshed fabrics and loose-fitting design is highly beneficial to improve air ventilation (Ho *et al.*, 2008; McCullough *et al.*, 1983).

The design of occupational clothing depends on common criteria, such as protection, functionality, performance, comfort, style, and usability (Kunštek *et al.*, 1998; Tanko and Anigbogu, 2012). In this regard, the work uniform should be designed not only to protect the worker's body from a stressful environment but also not to impede work performance. Construction workers are commonly exposed to direct sunlight and thus considered to be at a high risk of UV damage and even skin cancer (Chan *et al.*, 2015a). Thus, protection against the damaging UV rays is the second greatest criterion in new uniform design (Chan *et al.*, 2015a). The smart clothing design of the anti-heat stress uniform should also consider mobility, comfort, visibility, and safety of construction workers. For instance, porous reflective strips with different front and back design patterns can be used to balance air permeability and visibility.

2.4 Human wear trials in the laboratory settings

A comparison between the newly designed anti-heat stress clothing (AHSC) and a conventional trade uniform (TRADE) was drawn to ascertain the effectiveness of AHSC in alleviating heat strain and improving wearing comfort in a controlled laboratory setting.

Twelve subjects (ten males and two females) participated in the laboratory experiments inside a climatic chamber (LabTester, KSON, Taiwan) that simulated the typical outdoor hot and humid environments at 34.5 °C air temperature and 75% relative humidity. Each of them underwent a two-day wear trial while wearing AHSC or TRADE (Figure 3). Each trial included 30 min of pre-exercise rest, a period of intermittent running, 6 min of active recovery, and 30 min of passive recovery. Intermittent running was adopted because diverse construction work is largely intermittent by nature (Rappaport *et al.*, 2003). Physiological data including body core (T_c) and skin temperatures, heart rate (HR), as well as perceptual sensations such as comfort sensation, were recorded throughout the experiment. Mean skin temperature ($\overline{T_{sk}}$), mean body temperature ($\overline{T_b}$) , physiological strain index (PSI), and rate of heat storage ($\dot{S}$) were calculated according to the equations (3) (Ramanathan, 1964), (4) (Colin *et al.*, 1971), (5) (Tikuisis *et al.*, 2002; Moran *et al.*, 1998) and (6) (Lee and Haymes, 1995), respectively.

$$\overline{T_{sk}} = 0.3\,(T_{chest} + T_{forearm}) + 0.2\,(T_{thigh} + T_{calf}) \tag{3}$$

$$\overline{T_b} = 0.8T_c + 0.2\overline{T_{sk}} \tag{4}$$

$$\dot{S} = C_b \times \frac{m}{A_D} \times \frac{\Delta\overline{T_b}}{t} \tag{5}$$

$$PSI = 5 \times \frac{T_{ci} - T_{c0}}{39.5 - T_{c0}} + 5 \times \frac{HR_i - HR_0}{HR_{max} - HR_0} \tag{6}$$

where T_{chest}, $T_{forearm}$, T_{thigh}, T_{calf} are the skin temperature measured at the chest, forearm, thigh, and calf, respectively; $\Delta\overline{T_b}$ is the change in mean body temperature; C_b is the specific heat capacity of the body issue, named 3.47 $kJ\cdot kg^{-1}\cdot{}^{\circ}C^{-1}$; m is the body mass measured before experiment; AD in m^{-2} is the body surface area according to $A_D = 0.007184 \times Height(cm)^{0.725} \times Weight(kg)^{0.425}$ (DuBois and DuBois, 1916); t is the time interval in min; T_{c0} and HR_0 are the minimum core temperature and heart rate prior to exercise, respectively; T_{ci} and HR_i are the simultaneous core temperature and heart rate, respectively, taken at any time during treadmill exercise; HR_{max} is the maximum heart rate of the participant achieved; it is substituted into the equation if it exceeds 180 bpm.

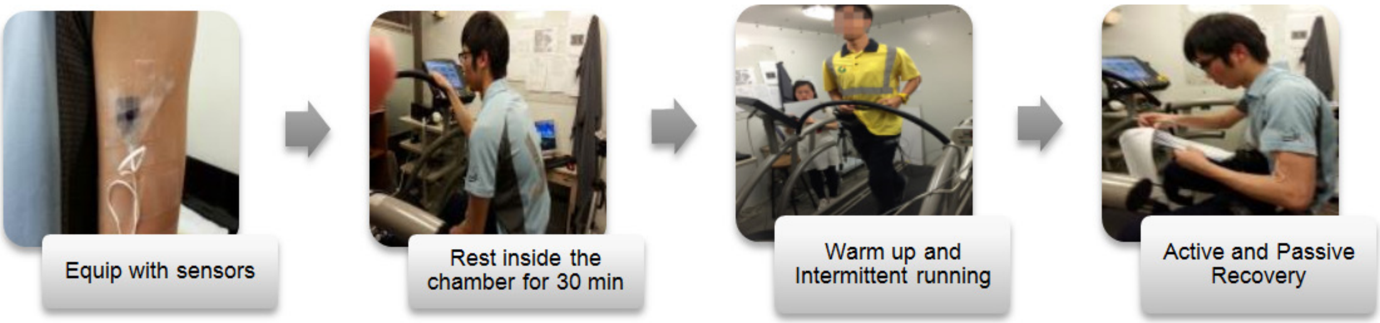

Figure 3 A typical run-down of the experiment

Figure 4 A typical run-down of the field survey

Table 1 Subjective assessments by 7-point Likert scales

Abbreviation/ Score	1	2	3	4	5	6	7
A1	Hot			Neutral			Cool
A2	Damp						Dry
A3	Clammy						Dry[2]
A4	Airtight						Breathable
A5	Thick and heavy						Thin and light
A6	Work performance interfered						Non-work performance interfered
A7	Uncomfortable						Comfortable

The differences in $\dot{S}$ and PSI between the AHSC and TRADE conditions were examined by a paired sample t-test. The differences in T_c, $\overline{T_{sk}}$, $\overline{T_b}$, and HR were examined separately by a two-way [Condition (AHSC vs. TRADE) × Time] ANOVA with repeated measures. The difference in comfort sensation between these two conditions was examined by Wilcoxon signed ranks. All these statistical analyses were conducted by SPSS (19.0) software programme.

2.5 Human wear trials in the field studies

A total of 189 male construction workers were invited to participate in the two-day wear trial (Figure 4). They were engaged from different trades, including timber formworks (48.7%), bar bending (31.7%), leveling (6.9%), plumbing (4.8%), bricklaying and plastering (4.2%), and painting (3.7%). They were randomly divided into two groups; half of them wore AHSC and the other half wore TRADE on the first day. The uniform type was reversed on the second day. Upon the completion of the wear trial, questionnaire surveys were administered to assess these two types of uniforms in terms of comfort, acceptability, and practicality. Seven items of subjective attributes were listed as bipolar descriptors on a 7-point Likert scale to assess the subjective perceptions on their work uniforms (Table 1). Furthermore, the participants after trying out both uniforms were asked to indicate their preference. For all data sets, the differences in subjective attributes between the two uniforms were tested by the Wilcoxon signed ranks test via SPSS (19.0) software programme.

3. RESULTS AND DISCUSSION

3.1 Developing an anti-heat stress work uniform

The design and engineering of the AHSC is a research from fundamental science into application technology to final product innovation. The most important capacity of the AHSC lies in the excellent heat transfer and moisture transfer capacity. The AHSC consists of a T-shirt (short-sleeved or long-sleeved) and a pair of long trousers. Coolmax and nest mesh fabrics are used for engineering the T-shirt. The fabrics comprise specially engineered polyester fibres to improve breathability compared with natural fibres (e.g., cotton). These fibres can draw moisture away from the skin through capillary action and increase evaporation over a wider surface area. The trousers are made from Dry-inside fabric, which incorporates moisture management technology by nano materials (Figure 5a). The moisture management textiles allow moisture to transfer away from the skin to the surface of the garment. These textiles possess high one-way transferability and

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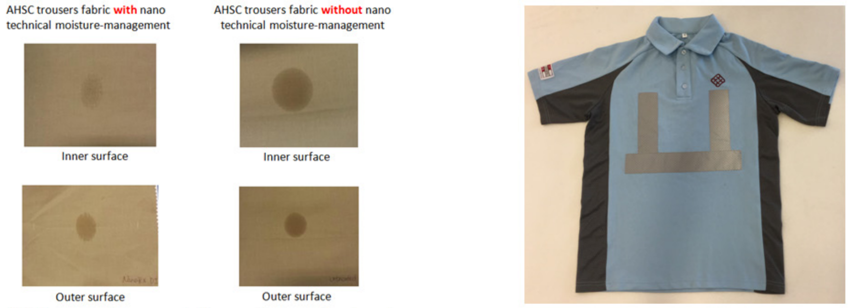
[2] Clammy-Dry describes the wetness of garments, while Damp-Dry means the skin wetness.



(a) Difference in sweat absorption and releasing with (left) and without (right) chemical treatment

(b) Meshed fabric on the side of the body

(c) Porous reflective strips

(d) Different front (left) and back (right) design

Figure 5 Special features of the anti-heat stress uniform

liquid moisture management capacity.

In addition to the thermal-moisture performance of the new uniform, the special features incorporated into smart design also consider workers' mobility, comfort, visibility, and safety of workers. For instance, the fabric of the newly designed uniform is lighter, thinner, and provides better UV protection than the conventional one. The meshed fabric (Figure 5b) and meshed reflective strips (Figure 5c) provide better heat dissipation and evaporation as well as ensuring safety and breathability. Different front/back design of the uniform ensures clear identification of whether the construction worker is standing in front of or behind the workstation (Figure 5d).

3.2 Performance assessment

3.2.1 Results of the laboratory experiments

Repeated measures ANOVA revealed a significant Condition × Time interaction for $\overline{T}_{sk}$ during exercise. That is, $\overline{T}_{sk}$ of participants wearing AHSC was significantly lower than those wearing TRADE when the running speed reached a high intensity. The beneficial effects of the AHSC uniform in reducing skin temperatures are apparent at certain time of exercise because of the pumping effect[3] resulting from the advantages of its fabric properties, loose-fitting design, and intense body movement. This induces air ventilation with a wider air gap between the skin surface and AHSC than TRADE.

During passive recovery, body temperatures of participants wearing AHSC were significantly lower than those wearing TRADE [Main effect of Condition: $T_{c(AHSC)} = 38.24 \pm 0.26$ and $T_{c(TRADE)} = 38.39 \pm 0.27$, $p = 0.031$; $\overline{T}_{sk(AHSC)} = 36.06 \pm 0.61$ and $\overline{T}_{sk(TRADE)} = 36.19 \pm 0.55$, $p = 0.044$; $\overline{T}_{b(AHSC)} = 37.79 \pm 0.28$ and $\overline{T}_{b(TRADE)} = 37.92 \pm 0.28$, $p = 0.006$; $PSI_{AHSC} = 4.29 \pm 1.09$ and $PSI_{TRADE} = 4.61 \pm 1.07$, $p = 0.012$]. These results implied that post-exercise evaporation contributed to a significant cooling effect because AHSC garments spread out sweat quickly and take away heat through sweat evaporation.

Particularly, $\dot{S}$ of participants wearing AHSC was significantly lower than those wearing TRADE across the rest-exercise-recovery cycle (52.4±16.15 for AHSC vs. 67.2±17.14 for TRADE, $p = 0.023$), indicating that evaporative heat dissipation with AHSC is more efficacious. Overall, the participants felt more comfortable when wearing AHSC in the entire test than those wearing TRADE [4±1 unit for AHSC vs. 5±1 unit for TRADE, $p = 0.033$]. The results support that wearing AHSC can buffer the detrimental effect of unpleasant subjective sensations and consequently encourage people not to take off these clothes in the heat (Heus and Kistemaker, 1998).

The major findings of laboratory experiments manifested that AHSC exhibited a remarkable reduction of physiological strain by 16.7% and body heat storage by 28.8% and an improvement in overall comfort by 20% (Figure 6).

3.2.2 Results of the field studies

The results of the field studies showed that the subjective evaluation of AHSC was much better than that of TRADE (Table 2). Thermal and pressure sensations and overall comfort were significantly better in AHSC than TRADE.

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[3] The term "pumping effect" refers to a phenomenon that the air exchange between the microclimate and the external environment is enhanced when the dressed person performs physical activities (Havenith *et al.*, 1990).

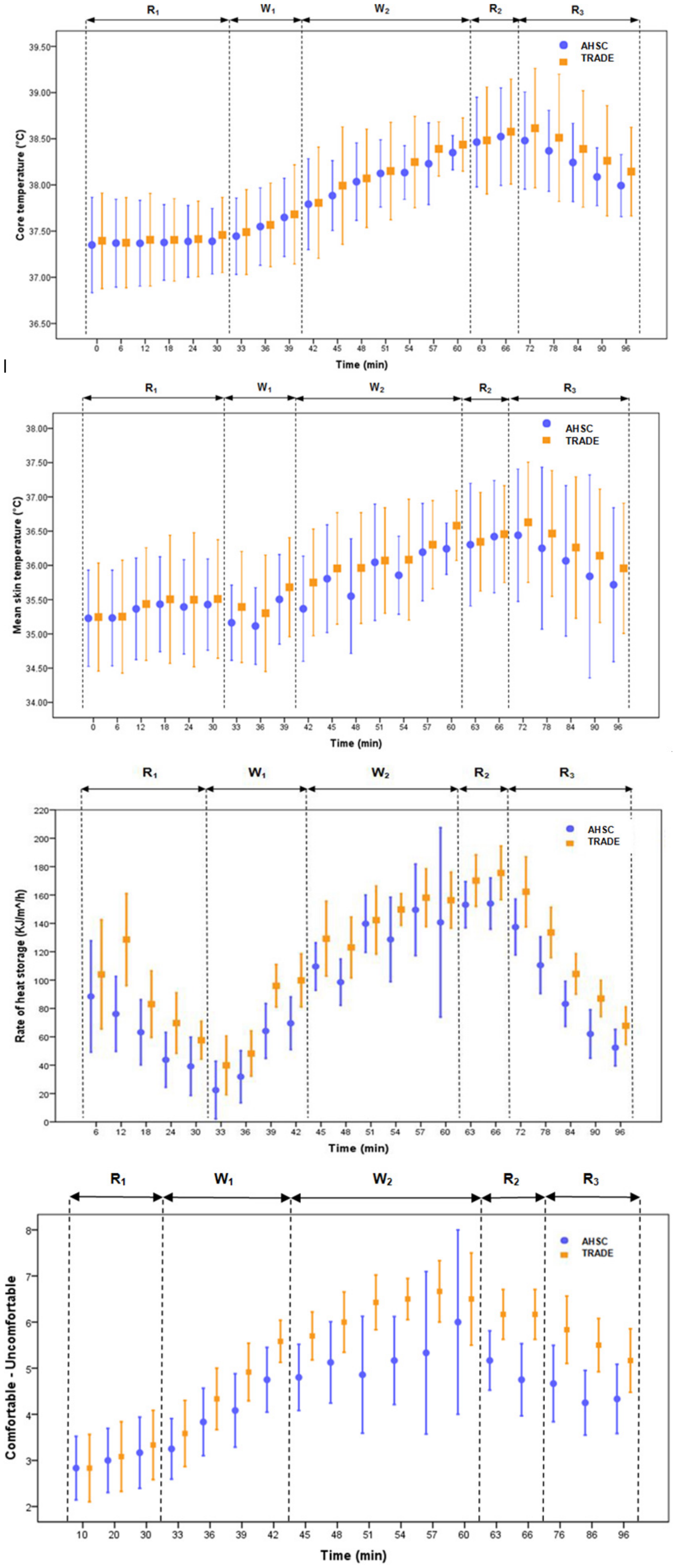

Figure 6 Effectiveness of the AHSC in terms of reducing body core temperature, mean skin temperature, rate of heat storage and improving wearing comfort

Note: R_1 – Pre-exercise rest, R_2 – Active recovery, R_3 – Passive recovery, W_1 – Warm up, W_2 – Work simulation

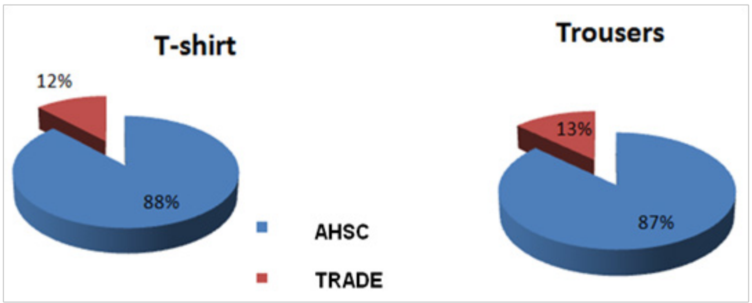

Figure 7 Construction workers' preference on two uniforms

Table 2 Subjective ratings on AHSC and TRADE (presented as mean values and standard deviation)

Attribute	Shirt		Pants	
	AHSC	TRADE	AHSC	TRADE
Thermal sensation				
Hot – Cool	3.87 (1.55)	2.33 (1.21)	4.20 (1.44)	2.42 (1.28)
Damp – Dry	3.71 (1.54)	2.17 (1.26)	4.16 (1.62)	2.38 (1.35)
Clammy – Dry	4.13 (1.42)	2.36 (1.30)	4.42 (1.53)	2.47 (1.42)
Airtight – Breathable	4.44 (1.56)	2.54 (1.24)	4.60 (1.48)	2.52 (1.41)
Pressure sensation				
Thick and heavy – Thin and light	4.87 (1.44)	2.78 (1.30)	5.04 (1.38)	2.73 (1.38)
Work performance interfered – Non job performance interfered	4.95 (1.51)	3.13 (1.40)	4.87 (1.53)	2.94 (1.43)
Overall sensation				
Uncomfortable – Comfortable	4.87 (1.57)	2.96 (1.36)	4.93 (1.53)	2.90 (1.43)
Dislike – Like	5.09 (1.50)	2.92 (1.39)	5.14 (1.45)	2.89 (1.47)

Note: A 7-point Likert scale was used to describe the subjective attribute, where 1=least preferred, and 7=most preferred. AHSC was rated significantly higher than TRADE on all sensory attributes.

Previous studies identified that thermal and pressure sensations are significantly related to clothing comfort sensation. For instance, the perception of coolness is a favourable sensation of wearers in summer (Li, 2001). Perceived wetness may increase clothing discomfort because of the increased friction between the skin and the moisture (Davis and Bishop, 2013). The ease of body movement by reducing fabric resistance to the body stretching (Senthilkumar *et al.*, 2012) is also important for construction workers performing various physical tasks. In view of this, over 87% of the workers preferred to wear the anti-heat stress uniform (Figure 7) because it kept them cool, dry, and comfortable without impeding work performance.

4. CONCLUSIONS

The practical value in reducing heat strain and improving comfort level by wearing appropriate work uniform is to promote the well-being of construction workers. Wearing the new uniform with excellent thermal and moisture performance may encourage people not to take off these clothes in the heat. In this regard, wearing the AHSC not only protects workers from ultra-violet radiation but also provides comfortable microclimate environment. As it can be expected, the well-being of construction workers would be enhanced when they wear the AHSC when working in hot weather, and so does the productivity.

The design and engineering of the AHSC may contribute to delivering an industry standard of heat stress controlling measure. The impacts of the AHSC to the construction industry have been expanded through a series of promotion and exhibition activities. Many organisations have expressed their interests in adopting this uniform for their apprentice or employees, which indicate that this uniform can be applied to other occupational settings and other countries.

ACKNOWLEDGEMENTS

This research was supported by the Research Grants Council of the Hong Kong Special Administrative Region, China (RGC Project No. PolyU5107/11E). The research team is indebted to the technical support from technicians of the Hong Kong Polytechnic University. Special thanks are given to all participants in this study for their participation and devoted effort in providing valuable and essential data. The support from the Construction Industry Council is deeply appreciated.

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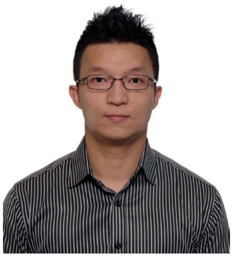

Prof. Del P. WONG is full professor at Sport Science Research Center, Shandong Sport University. He is an accredited sport and exercise scientist (BASES, UK) and chartered scientist (Science Council, UK). He was the former founding head of Department of Sports and Recreation at Technological and Higher Education Institute of Hong Kong (THEi) and founding director of Sports & Recreation Research Centre. In 2012, he received the Outstanding Young Investigator Award from National Strength and Conditioning Association (USA): being the first Asian to receive this award since the establishment of this association in 1978. In 2016, he led his research team and awarded the number one in the Higher Education Priority Academic Talent Development Program of Shandong Province with total funded amount for RMB 20 millions.

The research team also includes Dr. Michael YAM, Dr. Daniel CHAN, Dr. Edmond LAM, Dr. Yueping GUO, Dr. Wen YI, and Dr. Yang YANG of the Hong Kong Polytechnic University; Prof. Joanne CHUNG of the Hong Kong Institute of Education; Dr. Esther CHEUNG of Hong Kong University SPACE; and Dr. Wenfang SONG of Soochow University.

INDUSTRY PRACTITIONERS 1ST PRIZE

Mechanised Construction

Left:
Ir James Edward LAWTON, Ted
Gammon Construction Limited

Right:
Mr. Paul CHAN
Secretary for Development, HKSAR

NEW METHOD OF MECHANISED CONSTRUCTION FOR CONCRETE STRUCTURES

James Edward LAWTON, Ted[1,*], Andy Kwan-leung WONG[1] and Alex Kwok-fai FUNG[1]

[1]Gammon Construction Limited

Gammon Construction Limited has developed a method of mechanised construction for concrete structures, which enables established benefits of factory production on site, for areas including cost efficiency, working conditions, safety, labour requirements, quality control, programme assurance and sustainability. While timely delivery of projects, strong safety performance and caring for the environment are what the industry upholds, this method overcomes the drawbacks of traditional ones to help support the construction industry in Hong Kong.

Keywords: mechanisation, concrete structure, construction design management, precast,

1. INTRODUCTION

1.1 New challenges to our industry

Traditional methods of constructing concrete structures are currently overdue for change, as they are becoming less able to comply with the now increasing requirements in Hong Kong, i.e. speed of construction and safety. Imposing these new requirements is making construction more costly and labour intensive, compounded by a growing shortage of skilled labour.

1.2 Response

This new method of mechanised construction has been developed to supersede traditional methods, enabling desirable, established benefits of factory production on site, including consistent speed, quality, safety and cost control, which are all beneficial for programme surety and our environment. Safety by Design, or Construction Design Management, has been readily applied to the method by maximising planned working, which has inherently less risk than unplanned working. Similarly any residual risk has been mitigated in a systematic and controlled manner, more so than is possible with traditional methods.

Very significant improvements have been brought to our construction industry, by replacing traditional standing falsework with elevated platforms to construct concrete beams and slabs. This new method has been compared against the traditional one as being 4 times quicker, whilst requiring less than half the labour.

This represents a cumulative, eightfold decrease in time which our labour force is exposed to risk of accidents, corresponding to an eightfold increase in safety performance.

The initial cost premium for the platforms instead of standing falsework, was recouped after approximately 12 uses, without including programme benefits.

1.3 Method

Platforms span between columns, providing temporary support for the concrete casting, enable integrated access for safe working at height. This elevation is particularly efficient for highly elevated structures, whilst also providing clear access below, allowing other simultaneous construction activities, which would otherwise not be possible.

Only 30 hours after casting the concrete, the platforms could be removed for reuse. They have been designed to accommodate a central prop, or props, which remain in place to support the then immature concrete, until it has reached sufficient strength to be fully self supporting. Panels required to form the side profile of the beams are mounted on these platforms, which behave as jigs, ensuring that all beams and slabs are cast in the same, precise manner. These panels are also articulated, to permit safe, easy fixing and striking by hand, eliminating the hazardous traditional handling method by cranes.

2. APPLICATION

Mechanised methods are already present in construction, such as the use of jumpforms and slipforms for building core and wall construction, travelling forms for cantilevered bridge deck construction, gantries for pre-cast segmental bridge construction, strand jacks for heavy lifts, table forms for slab construction, curtain walling and numerous methods of precast concrete production.

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2.1 Bridge Projects

Figure 1 Stonecutters Bridge: Strand jacks used to lift 4,000 ton prefabricated deck from ground level, up to 80 meters and skidding horizontally into the final position

Figure 2 Shenzhen Bay, Deep Bay Link Bridge: Launching gantry used to erect 250 ton precast concrete, bridge deck segment

Figure 3 Kap Shui Mun Bridge: Incremental launching of concrete deck, produced in two stage casting bed

Figure 4 Castle Peak Road Bridge (Designed and built by Gammon Construction Limited): Example of travelling form requiring early formwork removal from a cantilevered pour, at concrete strength of only 15 N/mm^2, well before reaching its design strength of 60 N/mm^2

2.2 Building Projects

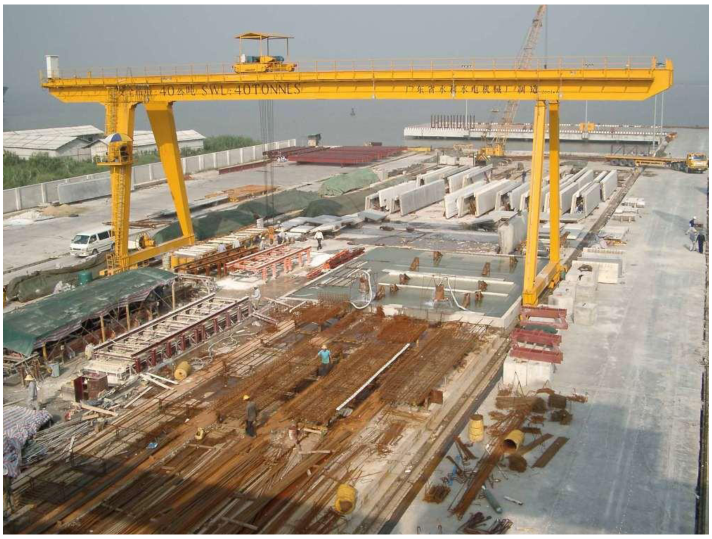


Figure 5 Production of architectural façade panels in a precast factory

Figure 6 Example of jumpform used in the construction of building core for IFC2

2.3 Features of mechanised construction

All of these applications (shown in Figure 1-6) require falsework designs which have been well engineered and planned beforehand and typically include the following features:-

2.3.1. Multi-discipline design, which may include building, civil, structural, mechanical and electrical engineering.

2.3.2. Only input of rebar and concrete are needed in an effective on-site factory to produce the required structure.

2.3.3. Provision of safe access whilst working at height and even over water where access from below is not feasible.

2.3.4. On-board, mechanised methods of self-launching, jumping and handling the formwork, reducing the requirement for cranage on the project. This also eliminates the risk associated with handling of heavy items by cranes and workers.

2.3.5. Fast production is achieved by virtue of the facts that all work activities have been carefully planned and even practised with protoypes beforehand. The work is repetitive, encouraging faster working and the concrete mixes may be specifically designed and developed to best suit the particular early setting and strength requirements.

2.3.6. Site management and supervision may focus on the current concerns, such as reducing the "cycle times".

2.3.7. In order to maximise the production rates, or minimise their "cycle times", these methods usually feature the early removal of formwork from the cast in-situ concrete structure, well before it has reached its design strength. Whilst this can be normally justified by calculation for civil engineering projects, the building regulations in Hong Kong normally do not permit this for building projects and applications for special exemptions are required, on a project by project basis. These require a more comprehensive appraisal of not only design, but the whole construction process on site and can generally be justified on the basis that:-

(a). Typical codified minimum periods for the early removal of formwork, were derived from conditions prevalent in the 1980s. Since then concrete technology, structural analysis, construction methods and site control measures, have developed significantly and improved, so when these improvements can be verified, they may be used to justify and enable earlier formwork removal.

(b). The Code of Practice for Structural Use of Concrete 2004 states that for sliding or climbing formwork, the time for striking being shorter than the recommended minimum standard may also be appropriate. An analogous example was the Castle Peak Road bridge successfully constructed by Gammon Construction in much more onerous cantilevered conditions (as shown in Figure 4).

3. APPLICATION IN AIRPORT CARGO HANDLING & PASSENGER TERMINALS

Figure 7 Overview of construction site showing (a) Foreground – Completed multi-span beam with temporary support props (Yellow colour); (b) Background – Platforms in position for the construction of the next beam (Yellow colour)

A typical beam span weights 240 tons. The use of traditional "Toyo" type of scaffold to construct this would require the erection and removal at height of 450 no. of Toyo scaffold frames, 150 no. of base jacks and 150 no. of U head jacks, including the in-situ construction and dismantling of a timber deck used to form the beam on top of the scaffold. This process has to be repeated for every beam to be constructed, resulting in repeated risk, timber wastage and damage to scaffolding components. It was impractical to construct the project using this method within the contract period and the alternative use of large pre-cast elements was also impractical, due to their large weight and corresponding cranage requirements. Accordingly, the platforms were designed with a lift weight of less than 10 tons to suit the readily available cranage.

3.1 Comparison between traditional and mechanised methods

A direct comparison was made on this project, between using scaffolding and mechanised construction, which is illustrated by the following photographs:-

Figure 8 TRADITIONAL – Untidy construction: Wall of scaffold blocking site access; intensive working at height and excessive risk of falling from height; numerous levels of boarded access of dubious integrity; potential for falling of loose materials during erection, dismantling or storage at height

(a) Safe access provided for working at height

(b) Unrestricted site access below

Figure 9 MECHANISED – Clean construction

Figure 10 MECHANISED – Multilevel beam construction: Integrated, safe access inside the platform between the columns, for safe working at height; steel formed concrete beams, precisely shaped with high quality finish

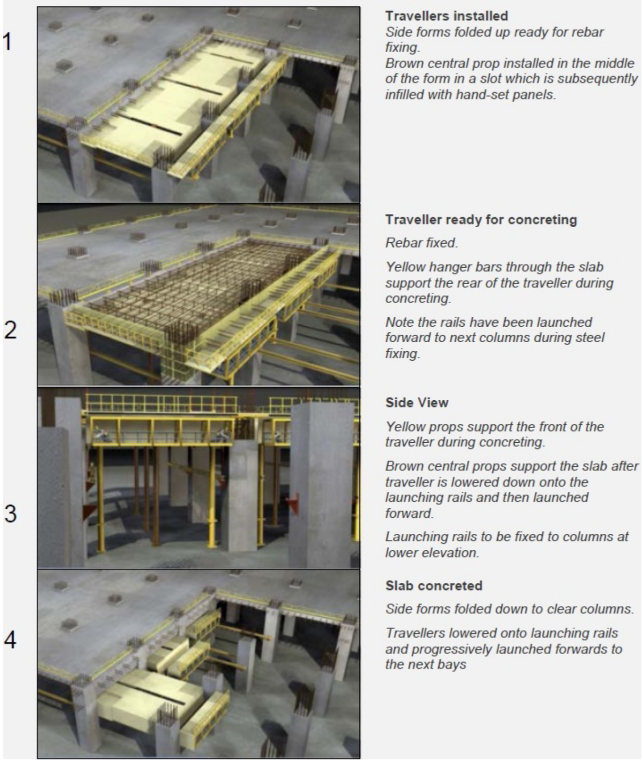
Figure 11 MECHANISED – Preparation for relocation of platforms: Platforms rolled out underneath beam, ready for craning to next beam; central prop remaining to provide support to beam until it has gained sufficient strength to become self supporting

Figure 12 MECHANISED – Relocation of platforms: Integrated, safe access at column heads for platform installation

Figure 13 MECHANISED – Subsequent floor construction: Precast I beams precisely located by side restraints and precisely cast on sides of in-situ main beams, still visible on the far left; precast floor slabs being placed from overhead on top of the I beams, necessitating their precise location by the side restraints

Figure 14 MECHANISED – Multilevel beam construction: Precast floor elements installed in the background

Figure 15 MECHANISED – beam construction: Safe access and multi-size beams casting



Travellers installed
Side forms folded up ready for rebar fixing.
Brown central prop installed in the middle of the form in a slot which is subsequently infilled with hand-set panels.

Traveller ready for concreting
Rebar fixed.
Yellow hanger bars through the slab support the rear of the traveller during concreting.
Note the rails have been launched forward to next columns during steel fixing.

Side View
Yellow props support the front of the traveller during concreting.
Brown central props support the slab after traveller is lowered down onto the launching rails and then launched forward.
Launching rails to be fixed to columns at lower elevation.

Slab concreted
Side forms folded down to clear columns.
Travellers lowered onto launching rails and progressively launched forwards to the next bays

Figure 16 Construction sequence

Note the rails are launched forwards to the next bay during steel fixing, so that the cycle time is minimised and there is adequate time to accurately locate the rails. The platform is launched to a position of similar accuracy, i.e. +/- 3mm.

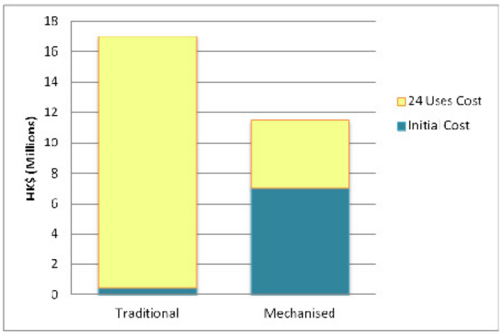
4. IMPROVEMENTS IN COST, PRODUCTIVITY, SAFETY & QUALITY

The structure of the air cargo handling terminal is now complete and a direct, on-site comparison has been made between new and traditional methods.

4.1 Cost

Figure 17 indicates that after approximately 12 uses, the mechanised method is more cost effective than the traditional method.

Cost Comparison



Less time
&
Less Labour
=
More Safety

	Traditional	Mechanised	Comparison
Days / use	27	7	1/4 of time
Labour (man days / use)	110	50	1/2 of men

8 times less man days for same construction

Figure 17 Eightfold increase in safety

4.2 Productivity and Safety

Figure 17 indicates that production is four times quicker and required less than half of the amount of workers. This equates to a reduction of man hours by a factor of eight, implying that exposure to risk of an accident is reduced accordingly, without additional allowance being made for safer access whilst working at height.

4.3 Quality

This is inherent in the use of steel moulds in terms of concrete surface finish and consistent accuracy of shape. This accuracy is enhanced because the formwork is fixed directly to the platform, which acts as a large template, ensuring all forms are always in the accurate position.

5. RATE OF PRODUCTION OR "CYCLE TIME"

The primary challenge to be met and make the method commercially acceptable, was to engineer a faster rate of production than that provided by other competing ones.

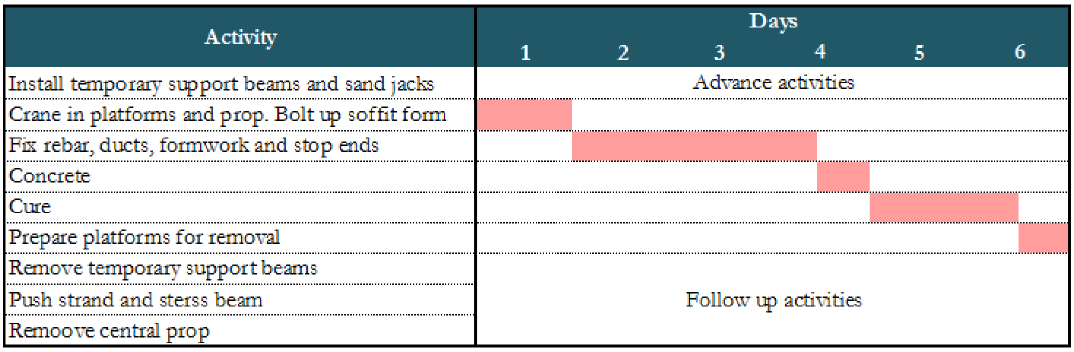
The simplified bar chart in Figure 18 shows the 6-day cycle time, with the critical, sequential activities in red. As many other activities as possible have been engineered to be independent of these critical activities, they may be completed in advance or after, with relatively abundant time to complete in a flexible way and to best suit availability of resources.

In order to maximise production rates, or minimise the "cycle time", this method utilises the early removal of formwork from the cast in-situ concrete structure, well before it has reached its design strength.

6. SAFETY BY DESIGN (CONSTRUCTION DESIGN MANAGEMENT)

Figure 19 summarises the Construction Design Management (CDM) process adopted for these projects.

Risk Reviews capture knowledge from all disciplines participating in the design, to identify and mitigate safety risks anticipated with future activities during the construction process. Risks are minimised by defining safe methods of construction which enable their removal, or alternatively residual risks are safely managed by the allocation of programmed control measures allocated to



Activity	Days 1	2	3	4	5	6
Install temporary support beams and sand jacks	Advance activities					
Crane in platforms and prop. Bolt up soffit form	🟥					
Fix rebar, ducts, formwork and stop ends		🟥	🟥	🟥		
Concrete				🟥		
Cure					🟥	🟥
Prepare platforms for removal						🟥
Remove temporary support beams	Follow up activities					
Push strand and sterss beam						
Remoove central prop						

Figure 18 Indicative cycle time for five span beam

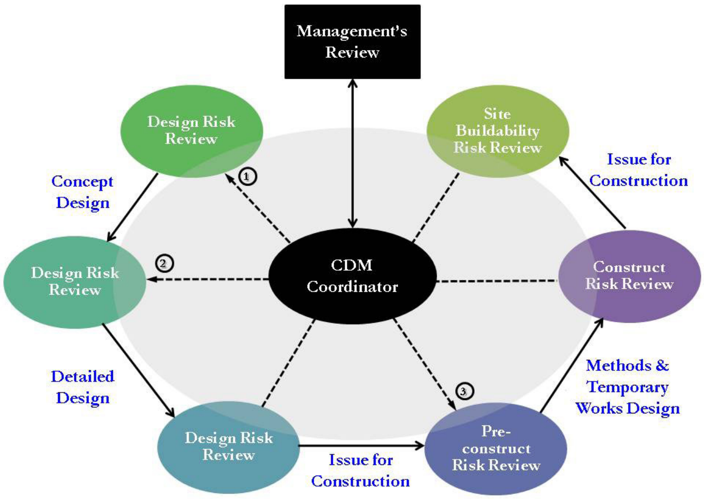


Figure 19 CDM process adopted: Route 1 – Develop design with Client and construct; Route 2 – Develop Client's concept design and construct; Route 3 – Construct Client's design

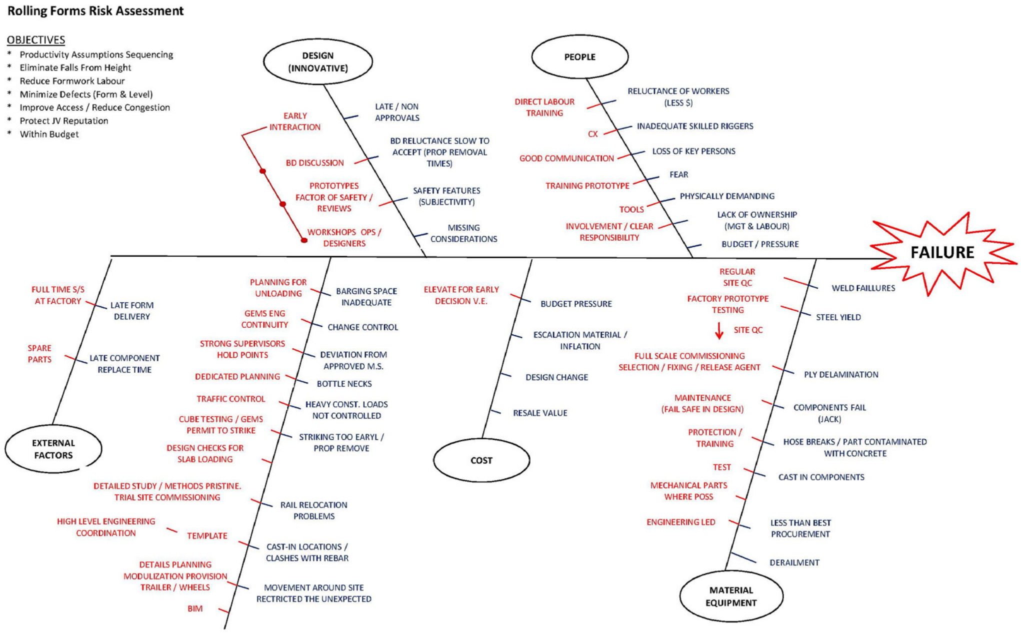


Figure 20 Initial risk assessment

competent nominees for their action. These deliverables are recorded on a Design Risk Register, which is progressively reviewed and updated during subsequent Risk Reviews, to become a life time record of the process.

Apparently, there were no any codes of practice relating directly to mechanised construction, so diligent management was required to ensure that the design complied with the requirements of all disciplines, primarily by ensuring that they were represented for design, design checking and safety reviews.

7. USE OF PROTOTYPES FOR TRAINING AND SAFETY

Figure 21 Airport Cargo Handling and Passenger Terminals: Prototype relocated to Hong Kong for training, safely at ground level

(a) Prototype in fabrication yard during bar jacking and launching trials

(b) Prototype relocated in HK for training of bar jacking and launching, safely at ground level

Figure 22 Station Development

8. SUSTAINABILITY

Figure 23 Traditional Standing Falsework: Consisting of scaffold, access routes and formwork

8.1 Reuse of platforms without damaged components

The use of steel to directly form the concrete virtually eliminates the need for timber and scaffold and may be reused almost indefinitely, either as a system for another project, or re-cycled. Side forms are integral with the platform so they are automatically relocated to the next beam as a module, without causing any damage.

By contrast, as is evident from Figure 23, traditional methods result in significant damage and wastage of timber and scaffold components, as they have to be assembled and broken down again, then transported to the next location to repeat the same inefficient process, whilst exposing our work force to numerous potential hazards. Considerable training, skill and high levels of supervision are required to mitigate many risks to our workforce, such as falling from height or injury due to falling objects.

Form ties and temporary cast-n anchorages have been designed to be fully recoverable, rather than being cast into and consumed in the concrete (Figures 24 and 25).

8.2 Greatly reduced consumption of timber

The combined use of precast floor elements and the steel platforms effectively removes the need for timber for floor construction. This generated a saving of 700 tons and 1800 tons of timber that would otherwise have been consumed in the Midfield Concourse Works and Cathay Pacific Air Cargo Terminal projects respectively.

Figure 24 Fully recoverable form ties over top of pour

Figure 25 A pair of recoverable anchor screws bolted to steel form ready for concreting

9. CONCLUSION

Further mechanisation and associated automation of construction may significantly improve our construction industry, particularly as this technology is now much more reliable and economically viable, which has already been realised in the automobile and aerospace industries.

This method was initially developed and used to enhance the construction of concrete structures typically found in large projects such as, logistic centers, airport terminals and station developments. It has the potential to benefit similar projects, particularly when construction can be of a repetitive nature and ideally, when opportunities may be secured from the client to improve buildability.

Application of this method in other types of structure, including other types of building structures and multi-span bridges, is currently being pursued.

ACKNOWLEDGEMENTS

The authors dedicate this work to Gammon Construction Ltd, in support of their initiatives to improve our construction industry and their support of innovation, including this New Method of Mechanised Construction. The authors are also grateful for the below parties for their support:-

1. Buildings Department, HKSAR Government – Approval of application for the early removal of soffit formwork.
2. Clients – Cathay Pacific, HK Airport Authority and MTR – Approval and support for use of this innovation on their projects
3. Clients' consultants – Meinhardt, Mott MacDonald, Arup and Aecom – Approval of designs
4. Independent Checking Engineers – Tony Gee & Partners and Hyder
5. Top Gammon management – Provision of resources for innovation and design in advance of tendering
6. Lambeth design office, Hong Kong – Innovation, design, promotion, development and implementation on site
7. Lambeth design office, Shenzhen – Production of computer generated animations for initial promotion to Gammon management, Clients and subsequent site training of operatives
8. Steelwork fabricators: Gammon Construction Services Department (CSD) Pristine, Hamco, Wing Chung, LUYU Construction Mechanical LTD., Hang Cheong Machinery Engineering Company Ltd., Hang Yue Aluminium and Steel Eng., Ltd., UCCA and East Gain – Development of prototypes and fabrication
9. Gammon CSD Concrete, Quon Hing Concrete Company Limited, Alliance Construction Materials Limited, Golik Concrete (HK) Limited, K. Wah Construction materials Ltd. – Development of concrete mix to best suit mechanized construction and load testing of sand jacks
10. Gammon Health & Safety Department – The incorporation of Safety into the design, notably during the development of the prototypes, "Safety by Design"
11. Gammon Foundations Division – Adaptation and use of load monitoring equipment to verify structural performance of central props and trusses
12. Projects Site Management – Site training of site engineers and operatives using prototypes, development of operations manuals and check lists

BIOGRAPHY

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Senior Engineering Development Manager for Gammon Construction Limited, with a balance of multi-discipline design and construction experience, gained from a range of major infrastructure and building projects. These include long-span bridges such as the Second Severn Crossing in the UK and Kap Shui Mun, Shenzhen Bay, Stonecutters and currently, Tuen Mun – Chek Lap Kok Link. Building projects include the Retail Bridges linking HK Central Station to IFC1 & 2, Cathay Pacific Air Cargo Handling Terminal, HKAA Passenger Terminal 3 "Midfield" and Express Rail Station XRL810A. Specialised in the design and management of alternative designs and construction methods. Recent years have included the development and application of new methods of Mechanised Construction for Commercial Buildings and Bridges.

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INDUSTRY PRACTITIONERS 2NDPRIZE

Development of City Air Purification System

ROADSIDE PERFORMANCE VALIDATION OF A NOVEL CITY AIR PURIFICATION SYSTEM

Jimmy C.K. TONG[1,*], Vincent S.Y. CHENG[1], Vincent W.S. LO[2]

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[2]Sino Green in Hong Kong Limited, Hong Kong

As the rate of urbanisation around the world, especially in China, accelerates, the air pollution problem becomes increasingly urgent. Controlling pollution sources from centralised locations like power plants, and distributed locations like vehicles, are both essential ways to tackle the problem. However, given the long process of revising regulations to control pollution sources and various localised, adaptive measures are relatively quicker solutions to curb air pollution. A novel City Air Purification System (CAPS) has been created by Arup and Sino Green, which aims to build a cleaner and healthier environment through tackling roadside pollution. The patent-pending invention has been built and tested in different environmental conditions, including Hong Kong and Beijing, both of which have a heavy road traffic and severe atmospheric air pollution. The encouraging results show that the system is capable of reducing the concentrations of air pollutants (PM2.5 and PM10) within the system by 30% to 70% under various ambient conditions.

Keywords: air pollution, purification, roadside health, public transportation.

1. INTRODUCTION

In many modern cities like Hong Kong, Beijing, and Shanghai, where roads are occupied by pollution-emitting vehicles, poor air quality is hazardous to the citizens, especially for those who have to expose to the outdoor air for an extended period of time. In addition, rapid urbanisation and industrialisation of developing cities require high energy consumption, worsening air pollution. Epidemiological evidence has indicated an adverse impact of atmospheric pollution on human health and overall mortality (Su, Chen, & Chan, 2011; Chart-asa & Gibson, 2015; Smith, Axon, & Darton, 2013). A common characteristic in these cities is the density of high-rise buildings, creating many narrow street canyons. The change of flow regime and accumulation of pollution, known as Street Canyon Effect, is one of the major problems due to the nature of modern cities (A.Mirzaei & Haghighat, 2010). It poses health problems to citizens on pedestrian walkways. These cities face difficulties in maintaining acceptable air quality level on the street. In Beijing, it was reported that 58 days in 2013 had an Air Quality Index (AQI) reading higher than 200 (Mei, 2014), which is classified as "very unhealthy" (China, 2012). Figure 1 illustrates the PM2.5 concentration all over the world (Voiland, 2010), and it can be clearly seen that quite a number of developing countries suffer from heavy air pollution, especially China.

At the National People's Congress in 2014, the Communist Party of China showed its determination to tackle air pollution by implementing new laws that would give great punitive power to the environmental enforcement agencies and enable independent environmental groups to operate in the country (Zheng, Yi, & Li, 2015). Long-term initiatives have been developed to improve air quality,

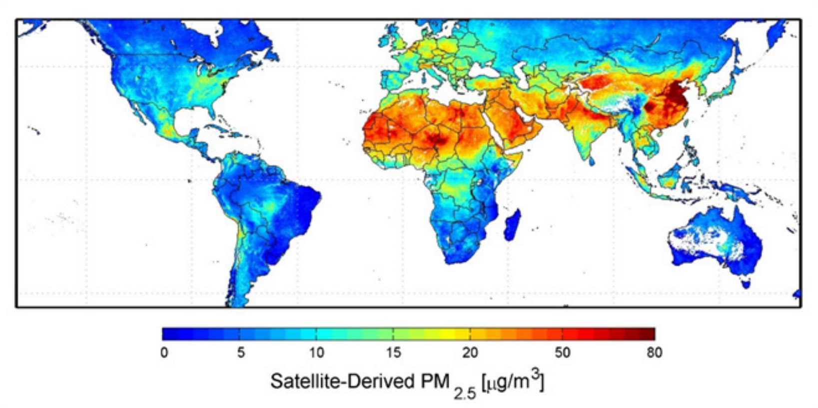

Figure 1 Satellite-derived Map of PM2.5 Averaged 2001-2006 (Voiland, 2010)

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including encouraging the use of less-polluting fuels, improving power generation and industrial processes, incentivising more efficient vehicles, and improving vehicle maintenance and emission standards. These initiatives are conducive to reducing air pollution to acceptable levels in the long run; still, it takes time for these initiatives to be implemented and to take effect. To serve immediate and pressing needs of curbing air pollution, Arup and Sino Green have developed a prototype, named the City Air Purification System (CAPS), which has been submitted for patent application. The goal of this system is to provide a ventilation system that filters out pollutants and generates purified air for pedestrians in proximity to the system.

The system was designed and simulated with fluid mechanic considerations so that it could build up an air curtain and a positive pressure, which acts like an invisible barrier to prevent roadside pollution from entering the system area. The system is also equipped with a medical-level filter in order to maintain an air quality inside the system area that complies with the World Health Organisation (WHO)'s PM2.5 guideline values (WHO, 2005). When the system was installed in Wan Chai, Hong Kong and currently inside Tsinghua University in Haidian district of Beijing, continuous performance data logging and on-site manual measurements were used to validate system effectiveness. The results showed that the system is able to provide clean air within its own area.

2. DESIGN OF THE INVENTION

Concept and Design

Hong Kong and Beijing have different characteristics in terms of city development and environmental conditions. In Hong Kong, the urban environment is dense and compact; busy and congested traffic means that pollutants generated by vehicle exhaust, building exhaust and other pollutants sources are trapped in narrow streets, which are lined with tall buildings on both sides, resulting in the Street Canyon Effect (Yim, Fung, Lau, & Kot, 2009). The dispersion of the pollutants, subsequently becomes weak and limited, making street-level air pollution even worse. On the other hand, Beijing faces more severe atmospheric air pollution, but the city's building development is comparatively less compact. In both cases, people exposed to such polluted air may suffer from higher health risks, especially respiratory problems like asthma or even lung cancer (Su, Chen, & Chan, 2011; Chart-asa & Gibson, 2015; Smith, Axon, & Darton, 2013).

To mitigate the underlying air pollution problem in cities like Hong Kong and Beijing, feasibility studies were carried out to investigate the effectiveness and practicability of different design solutions. Subsequently, based on the considerations of usability and flexibility, CAPS, a patent-pending bus-stop-like prototype, was created. This system is equipped with a High Efficiency Particulate Arrestance (HEPA)-type filter and a fan. With the filter, up to 95% of PM2.5 and larger suspended particulate matters in the ambient air can be filtered away. The purified air is then delivered to the occupied area of the system through the fan. This air circulation is able to provide a localised clean air zone for pedestrians within the system. The system can benefit people who are standing or waiting in the outdoor polluted environment, especially on the roadside, by providing improved breathing air quality.

Engineering Simulation and Validation

Having established the ideas and concept for the design of CAPS, a computational fluid dynamics (CFD) model was developed to carry out a feasibility study and performance optimisation of the system, which aimed at identifying the optimised operating condition to maximise overall filtration effectiveness, while minimising energy consumption. The CFD modelling technique allowed predetermination of the system's workability and identification of the optimised system operation combinations prior to the production of a standard system, preventing unnecessary wastage and shortening the overall production time.

In the CFD model, the effects of turbulence in the ambient flow environment have been taken into account. A ϰ−ω based turbulence model was used in the design in view of its particular advantage over the traditional ϰ−ε method in the fluid–wall boundary layer. The model adopts the Reynolds-averaged Navier-Stokes approach, where the motion of fluid flows is described in time-averaged form. The equations of mass and momentum conservation are:-

(1) $\frac{\partial u_i}{\partial x_i} = 0$; and

(2) $\rho \frac{\partial u_j}{\partial t} + \rho \left(u_i \frac{\partial u_i}{\partial x_i} \right) = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left((\mu + \mu_t) \frac{\partial u_i}{\partial x_i} \right) j = 1,2,3$

where μ and μ_t in Equation 2 are the molecular and turbulent viscosities respectively.

The final equations required for the solution are used to deal with turbulence levels. Transport equations for the turbulent kinetic energy ϰand the specific rate of turbulence dissipation ωare

(3) $\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_i k)}{\partial x_i} = P_k - \beta_1 \rho k \omega + \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right]$

(4) $\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_i \omega)}{\partial x_i} = \alpha \rho S^2 - \beta_2 \rho \omega^2 + \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_{\omega 1}} \right) \frac{\partial \omega}{\partial x_i} \right]$

$$+ 2(1 - F_1) \rho \frac{1}{\sigma_{\omega 2} \omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i}$$

The non-linear and coupled equations (Equations 1 – 4) were solved in the CFD model over a multitude of finite-sized elements that constitute the solution domain.

In the CFD model, a wide range of different scenarios and operating conditions were simulated and investigated. Compared with indoor environmental studies, it is much more complicated to use the CFD model in this system analysis because, other than possible system variability, uncontrollable ambient factors such as external wind and background ambient pollution level would affect the system performance. Under different external conditions, simulations were carried out to investigate the impacts of different system operating parameters on the overall filtration effectiveness. Finally, the optimisation of the system's operation in terms of the air pollutant level inside the system area, the air balance of the air delivery system and the fan operating speed were identified, resulting in the current version of CAPS.

Prototyping

In addition, 3D printing technology was employed in the development process to bring the design of the system to life. Making a 3D model helped to speed up the overall process of producing the prototype, through customising the physical dimensions of the system to accommodate the users and the filter and fan, fine-tuning the appearance of the prototype, and preliminarily checking its constructability. This prevents unnecessary rework and thus reduces the costs and production time of the real prototype.

After carrying out the optimisation process through using computational simulations and the 3D printed model, the prototype was manufactured. The prototype, in addition to the fan and filter, was equipped with an aerosol monitoring system that allowed continuous air quality data logging and on-site air quality measurements. All the equipment was sourced from international suppliers.

The aerosol monitoring system enables the prototype to perform real-time data collection of the air quality inside the system area, which allows system performance analysis with the following features:

- Real-time dust monitor
- Light scattering laser photometers
- Simultaneous measurement of size-segregated mass fraction concentrations corresponding to PM1,PM2.5, PM4 and PM10
- Continuous, unattended, 24/7 outdoor monitoring
- Suitable for industrial site safety and hygiene surveys

In addition, an electronic device connected to the government's air quality health index website was also fitted to the prototype, to display the hourly air quality data from the published roadside air monitoring stations, enabling on-site referencing of the air quality inside the system and the ambience. Figure 2 below illustrates the development process of the prototype.

3. ROADSIDE TESTING

Taking into account of the data comparison of possible installation locations and Hong Kong Government's official roadside air monitoring stations located in Central and Causeway Bay (EPD, 2015), the prototype was installed in Wan Chai, one of the busiest districts in Hong Kong that is situated between two official air monitoring stations. The installation location of the prototype has similar traffic conditions and surrounding built environments, which are characterised with heavy traffic conditions and high roadside pedestrian usage, and surrounded by high-rise buildings such as Hopewell Centre, QRE Plaza and Wu Chung House. These conditions make the ambient air quality data of the prototype similar to that of the government's official stations.

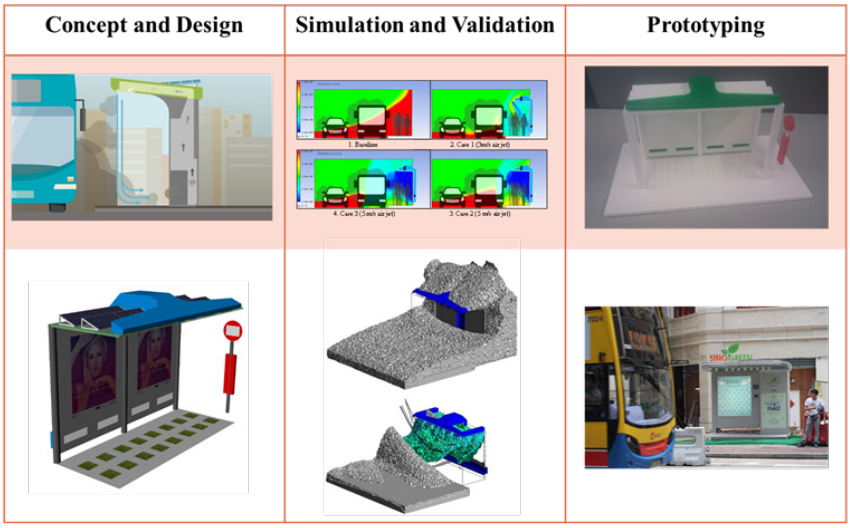

Figure 2 Development Process of the City Air Purification System

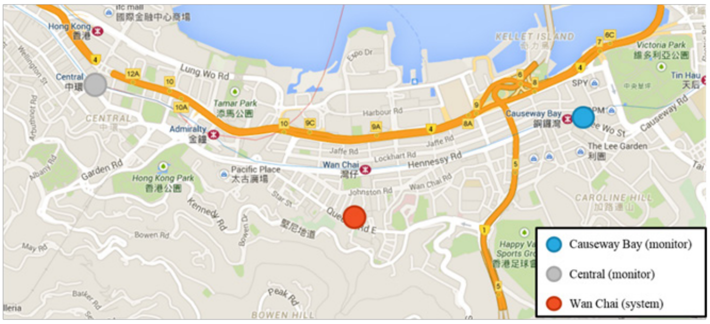

Figure 3 Installation Location of the Prototype on Google Map

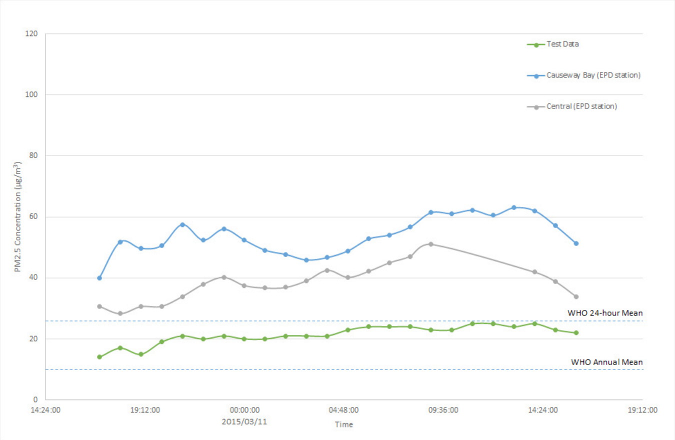

Figure 4 Measurement Results for Baseline Condition

Roadside testing of the prototype in Wan Chai was performed for around two months (from March to May 2015) to analyse the real system performance with respect to the ambient air quality data inside the system area. The testing was conducted in two ways – continuous data logging and manual on-site measurement.

As the prototype location and the two nearby official roadside air monitoring systems (located in Causeway Bay and Central) share similar characteristics in terms of traffic conditions, pedestrian usage and built environment, the air quality data measured by official roadside air monitoring systems were used as a reference for evaluating the system performance of the prototype. Figure 3 indicates the installation location of the prototype.
Figure 3

Continuous Data Logging

Before testing the system performance, the aerosol monitoring system was used to measure the baseline environmental condition at the prototype installation location. It was set to log the air quality data for two days so that the ambient air quality profile at the localised area of the prototype installation location can be analysed against the data from the two nearby official roadside air monitoring stations, i.e. Causeway Bay and Central.

Reference was also made to PM2.5 pollution levels along the tramway (Ng, Fung, Lau, & Lau, 2015), from a study that measured the spatial distribution of PM2.5 concentration along the tramway that runs from West (Kennedy Town) to East (Shau Kei Wan) on Hong Kong Island along its northern shoreline. The tramway passed through the exact locations of the two official roadside air monitoring stations in Causeway Bay and Central. The report identified the pollution hotspots along the tramway and revealed that there is a variation of PM2.5 concentration of about 38% between the Central and Wan Chai districts. It provides a basis for comparing the prototype roadside testing with the official roadside air monitoring stations against a set of comprehensive data and analyses of PM2.5 concentration along the northern shore of Hong Kong Island.

From the comparison analysis between the site ambient air quality and the official roadside air monitoring stations as shown in Figure 4, similar air quality variation patterns were found. In addition, a consistent difference between the site air quality and the official roadside air monitoring stations was also identified. The results revealed that the difference between the measured baseline data with the published roadside monitoring stations at Causeway Bay and Central was around 55% and 40% respectively, which were used as a correction factor to estimate the ambient air quality of the prototype installation location on the basis of the published data from the two nearby roadside monitoring stations.

After that, the air quality inside the system area was monitored at different settings of the prototype system, including the flow rate and the air delivery angle. Under different settings, the air quality data were measured for 3-7 days to obtain a detailed analysis of the system performance against the ambient air quality conditions.

Manual On-site Measurement

To understand the system operating performance more comprehensively, manual on-site measurements were also conducted around two to five times a week. During the measurement, the air quality inside the system area and the immediate ambient conditions were measured within the same period. The objectives of the manual on-site measurements were to explore the air quality distribution inside the system under different external air conditions, to identify the impact of the external environmental conditions on the overall prototype system performance, and to evaluate system effectiveness under different system settings.

To achieve the aforementioned objectives, a testing protocol was developed to conduct the measurement. During each on-site measurement, air quality measurements were taken at 15 predefined measurement points inside the system, covering different people's heights at different standing locations inside the system. The measurement of air quality not only covered the breathing zone of typical adult height (~1.5m), but also children's heights (typically ~0.5m). These 15 predefined measurement points were designed to enable 3D mapping of the air quality distribution pattern inside the system area across the entire system space, such that the width, length, height and the identification of healthy environment that can be maintained at both the adults' and children's levels.

The immediate ambient conditions were also measured every time before and after the on-site measurements, in order to evaluate the impact of external conditions on system performance. The ambient measurements included the wind direction, wind speed, ambient air temperature and air quality. The ambient measurements were taken at four different predefined locations that were about 1-2 m apart from the prototype. Besides, during each measurement, the external conditions, such as the weather conditions and traffic conditions, were also observed to facilitate the explanation of the measured data and some special conditions of the data log. The measurements of internal and external conditions were conducted within ten minutes to reflect the real-time air pollution level in a particular time slot.

After verifying performance of the prototype in Hong Kong, the prototype was relocated to Beijing for roadside testing in different environmental conditions in July 2015. A similar approach, including continuous data logging and manual on-site measurements, was adopted to verify system performance.

By conducting on-site measurements with the established testing protocol, different system operation settings were tested. Besides, by adjusting the fan speed and the air delivery angle each time before testing, the air quality inside the system was measured and compared with other different scenarios. This exercise also enabled the identification of the filter conditions. If the filter performance deteriorates due to aging of the filters and blockage by the filtered particles, the flow rate and the filtering effectiveness would be reduced. All such signs would be reflected in the data collected during the on-site measurements, providing alerts to clean or even replace the filtration system.

4. RESULTS AND CORRELATION

Based on the roadside testing including the continuous data logging and on-site measurements, data were extracted and analysed for various purposes, including:

1. Evaluating the uniformity of the air quality distribution inside the system area;
2. Investigating the overall prototype system performance by comparing with the ambient air quality baseline; and
3. Correlating the roadside testing data with the simulated models.

Evaluation of Uniformity of Air Quality Distribution

In accordance with the developed on-site measurement protocol, measurements were taken in 15 predefined measurement points inside the system area, which allowed three-dimensional analysis of the uniformity of the air quality distribution. Out of these measurement points, three levels covering the air outlet, adult height and children's height in different locations inside the system were measured.

The measurement results revealed that the air quality distribution inside the system area are uniform and able to maintain at an acceptable level according to the WHO's guideline values of PM2.5 (WHO, 2005). Even under strong external wind and high ambient pollution condition, the measured data showed that the quality air can still be evenly distributed, effectively delivering the filtered air to the breathing zones of different people's heights. The recorded results showed that the difference between the maximum and minimum air quality level inside the system area under the worst case scenario, i.e. high ambient pollution with strong wind, was kept at about 20%. The results also revealed that higher uniformity can be achieved under better scenarios, i.e. lower ambient pollution level and weaker wind conditions.

Investigation of Overall Prototype System Performance

Using the continuous data collected by the aerosol monitoring system, the prototype system performance in terms of the air quality level inside the system area was investigated and compared against the air pollution data from the two nearby official roadside air monitoring stations as reported on the EPD's website (EPD, 2015), the estimated ambient conditions of the prototype installation location, and the WHO's guideline values of 24-hour mean and annual mean for PM2.5 (WHO, 2005).

As the monitoring system was in operation for about two months, the data covered a wide range of different external environmental conditions and different system settings. Comprehensive data analyses were carried out to evaluate the overall prototype system performance and the impact of external conditions on system performance. In general, the prototype is able to maintain an acceptably healthy environment inside the system area, with a PM2.5 level that is well below both of the WHO's hourly-mean and long-term guideline values (WHO, 2005). The data analysis also found that higher air circulation rate of the system yielded better air quality inside the system area.

Two-month data were collected and analysed from the prototype operation. Taking the time series collected between 15th and 16th March 2015 as an example, as illustrated in Figure 5, the average pollution level recorded from Causeway Bay and Central EPD stations were 48µg/m^3 and 32µg/m^3 respectively. The estimated Wan Chai pollution level fell within the WHO 24-hour mean (25µg/m^3) (WHO, 2005). Under such conditions, the prototype demonstrated its purification ability by consistently reducing pollution to a level below the WHO annual mean (10µg/m^3) (WHO, 2005). Data recorded have shown that the prototype system is able to reduce concentrations of PM2.5 by 30-70%.

As shown in Figure 6, another dataset, collected from the period of 12th – 13th April 2015, was retrieved for analysis. The monitored data from the official EPD stations showed that Causeway Bay and Central peaked around 80 µg/m^3 and 60µg/m^3 respectively during busy traffic hours. It is observed from the estimated pollution level at Wan Chai that under peak hours, although the air quality did not comply with WHO 24-hour mean (25µg/m^3) (WHO, 2005), the prototype still demonstrated its pollutant-reduction ability after operating for a month. The pollution level can be maintained below 25µg/m^3 and further improved under the WHO annual mean level (10µg/m^3) during a non-peak period at the evening.

In summary, it was observed that the air quality inside the system area was aligned with that of ambient air quality. In other words, the peaks and valleys of the air pollution data happened at more or less the same time of day. Yet, during the high-pollution period, the air quality inside the system can still be maintained below the WHO's 24-hour mean PM2.5 guideline values (WHO, 2005). In short, it can be concluded that the prototype system is able to reduce the concentrations of pollutants by 30-70%.

Besides overall system effectiveness, operation-related aspects such as sounds and people's comfort were also evaluated. In general, as the prototype operated on the roadside, close to traffic and a nearby construction site, the noise generated by the operation of the prototype was nearly undetectable across all operational conditions. It is therefore proven that the prototype not only provides a healthy environment inside the system, but also thermal and aural comfort.

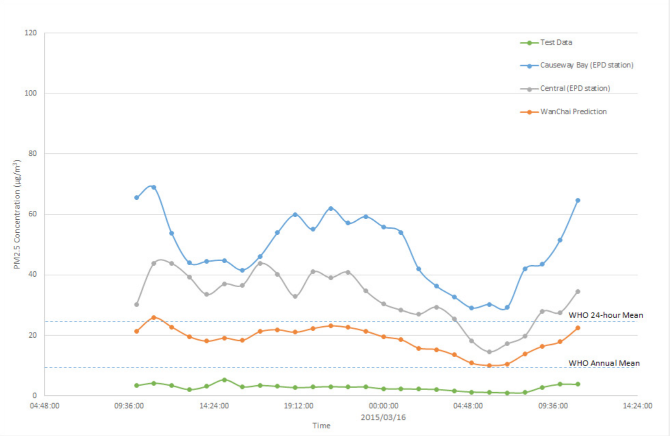

Figure 5 Time series record (15th and 16th March 2015)

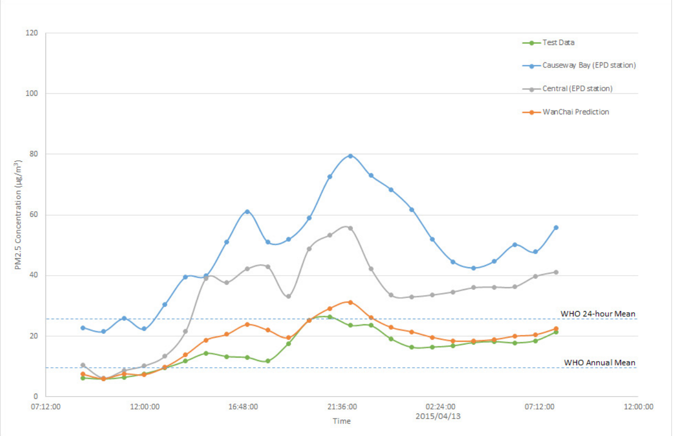

Figure 6 Time series record (12th and 13th April 2015)

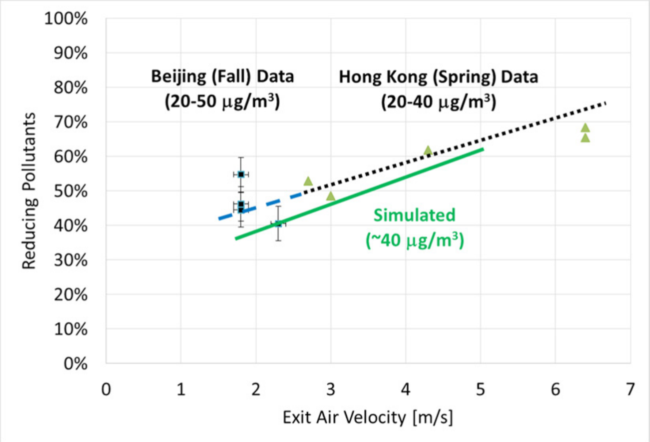

Figure 7 Correlation Results between Measured Data and Simulated Data

Correlating the Roadside Testing Data with the Simulated CFD Model

A correlation analysis of the roadside testing data and the simulated data of the CFD model was conducted using measured data from Hong Kong and Beijing. As shown in Figure 7, the results showed that the simulation model can accurately predict the real situation with the difference of less than 10%. Moreover, it was also found that the roadside testing data had a similar trend as simulated data across various system settings, i.e. from low to high circulation rate. From the analysis, it was identified that the effectiveness of the prototype increased with the supply flow rate of the filtered air.

In Wan Chai, Hong Kong, in order to tackle the Street Canyon Effect and roadside pollution, the prototype was set on high outlet velocity to maintain an effective air curtain. In Tsinghua University, Beijing, where the Street Canyon Effect is less prevalent due to lower tall-building density, the prototype was set on lower outlet velocity. The data collected from Tsinghua aligned with that from Hong Kong, substantiating that the prototype is capable of reducing pollution under different environmental conditions.

Having confirmed the accuracy of the simulation model with on-site roadside testing results, the model can be used to predict system effectiveness under different external environmental conditions and system settings. System optimisation can therefore be done by evaluating different scenarios so that the effectiveness of the whole prototype system can be maximised. In other words, the optimised operation conditions, i.e. using the smallest fan power to maintain an acceptably healthy environment inside the system, can be identified.

5. FUTURE DEVELOPMENT AND POTENTIAL APPLICATION

The prototype can possibly be developed into the next generation and fitted with additional features. The major objective of developing the next generation is to achieve low-carbon or even zero-carbon operation while maintaining the air quality inside the system area at an acceptable level.

In addition, the weight and cost of the system can be reduced if its life span can be lengthened for commercialisation. Based on the current data analysis, the system can now reduce the concentrations of PM2.5 by 30%-70%, depending on the ambient pollution level. This strong performance means that the prototype could be mass-produced and applied in major Asia cities such as Beijing, Shanghai, Ho Chi Ming City and Singapore, all of which are tackling roadside air pollution. In addition, given studies that have shown an interwoven relationship between air pollution and human health (Su, Chen, & Chan, 2011; Chart-asa & Gibson, 2015; Smith, Axon, & Darton, 2013), the prototype could also be equipped with newly-developed technology that enables DNA-based testing for air pollution (Chen, *et al.*, 2014). As the wide application of the prototype could provide a much better roadside environment for the citizens and mitigate potential health problems due to air pollution, these enhancements would turn the prototype into a valuable asset for many cities around Asia and worldwide.

The air cleaning concept from CAPS could also be adopted into different forms, benefiting wider areas in cities. The patent covers different forms of the prototype, including building canopies, outdoor kiosks and central underground filtration systems. It is also feasible to retrofit the prototype onto existing buildings. Regardless of the form, the ultimate objective of CAPS is to provide a cleaner and thus a more livable outdoor environment for urban residents.

6. CONCLUSION

Rapid urbanisation and industrialisation especially in developing countries require large amounts of energy, posing air pollution problems and thus health issues to humans. In modern cities like Hong Kong, Beijing, and Shanghai, the air pollution problem is particularly severe, because the high density of high-rise buildings results in the Street Canyon Effect that traps and accumulates air pollutants in narrow streets. People walking in proximity to or being exposed to such street spaces or roadside are breathing in polluted air that is hazardous to health.

To mitigate the underlying issues, the patent-pending CAPS prototype, whose performance was proven by CFD simulations, has been developed and tested. When the prototype was installed in Wan Chai district of Hong Kong and inside Tsinghua University in Haidian district of Beijing, for two and six months respectively, roadside testing, including continuous air pollution concentration data logging and manual on-site measurements, was carried out to validate the system performance. The measurement results showed that the roadside testing data align with the simulated data and revealed that the prototype is able to reduce the concentrations of air pollutants by 30% -70%, providing a healthy environment inside the system area.

ACKNOWLEDGEMENT

The patent-pending City Air Purification System (CAPS) was developed by Arup and Sino Green.

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BIOGRAPHY

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Dr. TONG is an Associate at Arup focusing on Building Sustainability. A recognised industry leader within the energy business, Dr. TONG has applied his expertise in energy systems in various sectors, including wind and renewable energy, infrastructure and building services, and product and system development in the manufacturing of electronics, ventilation equipment, and filtration equipment for more than 16 years. He obtained a PhD specialising in computational fluid flow and heat transfer from the University of Minnesota. He is also a guest lecturer at several universities in Hong Kong on the subject of energy and sustainability and co-authored book publication and book chapters and publications in archival, refereed journals.

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Dr. CHENG is the director of Building Sustainability Group of Ove Arup & Partners Hong Kong Ltd. He has over 20 years of professional experience in building energy efficiency. He has extensive knowledge and experience in sustainable building environment design and government consultation studies, including Taiwan EPA's Low Zero Carbon Pilot Project, CEPAS of Buildings Department, Life Cycle Assessment Tool of EMSD and Air Ventilation Assessment of Planning Department. Dr. CHENG also specializes in sustainable master planning, low/ zero carbon design, LEED & BEAM Plus certification, life-cycle analysis and Air Ventilation Assessment. He is a HKPGBC council member and also a member in the advisory committee of School of Energy and Environment, the City University of Hong Kong.

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Mr. LO is a General Manager of Sino Green in Hong Kong Limited, which supports the development of a sustainable community through green architecture, management and education. In addition to leading the engineering teams on property development projects, Mr. LO has worked with consultants and the academia on research and application of green initiatives into actual operation, including the patent-winning CAPS (City Air Purification System), in-building hydropower system, food and organic waste purification and tidal power.

Left:
Ir S.S. LEE
Former Chairman of the CIC

Right:
Prof. ZHU Jingxiang
Chinese University of Hong Kong

ACADEMIA 1ST PRIZE

Z-Panel System - Lightweight Prefabrication

Z-PANEL - PREFABRICATED LIGHTWEIGHT ARCHITECTURAL SYSTEM IN PLATEAUS

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Extreme climatic conditions of thin mountain air, long freezing winter and rapid temperature changes in summer in plateaus require buildings of special concern to the surrounding environment. In 2015, the Architecture Integrity and Innovation Association (AIIA) of the Chinese University of Hong Kong developed Z-Panel system, a prefabricated lightweight architectural system for plateau area, and applied to a new school in Lawuga Village, Yushu, Qinghai. By introducing the system and the built project, this paper illustrates a sustainable building possibility, which is not only applicable to plateaus but all alternatives.

Keywords: lightweight, prefabrication, plateau, yushu.

1. INTRODUCTION

In 2013, Architecture Integrity and Innovation Association (AIIA), a research team from the School of Architecture, The Chinese University of Hong Kong was committed for a charity school project in Yushu Autonomous Prefecture, Qinghai Province, which experienced a 7.1MS earthquake in 2010.

The site is located at an altitude of 3900 meters above sea level. It has a typical plateau climate with prolonged freezing winter and rapid temperature changes in summer. Construction of buildings on the unveiling plateau is required to take into account its relationship with the special environment. Besides, considerable structural demand needs to be met in terms of snow, wind and earthquake. The construction process should consider the plateau environment of fragile ecology system, thin mountain air, and limited construction period (construction works is forbad from October to April because of inclement weather). A comprehensive architectural proposal is required with considerations of sustainability, users' comfort and construction methods.

Figure 1 Lawuga School and Village

Site visit was carried out before the detail design process. Locating in the plateau area, Yushu does not have advanced manufacturing technology. However, the highway network connecting to surrounding cities is well developed. The school site is adjacent to the No. 214 state road. Large-scale construction machines such as crane are available in the city, which might be used for the rescue and reconstruction activities in previous years. All these criteria provide excellent conditions for adopting prefabrication in Yushu.

Founded and led by Prof. ZHU Jingxiang since 2008, AIIA has focused on investigation and design works on prefabricated lightweight architectural system, attempting to provide prototypes by integrating the manufacture strengths and latest technology of the production chain. From 2009 to 2015, three rural primary schools in the Mainland China, four eco stations for natural reserves, and a primary school in Mathare, Kenya were completed.

After conducting corresponding researches and studies, the AIIA research team found the answer - Z-shaped panel. It is a simple but effective response to all-round considerations. More importantly, it leaves enough flexibility for development of different architecture with varied scale and programme. The fundamental element of Z-Panel System is large panels with a sectional Z-shape.

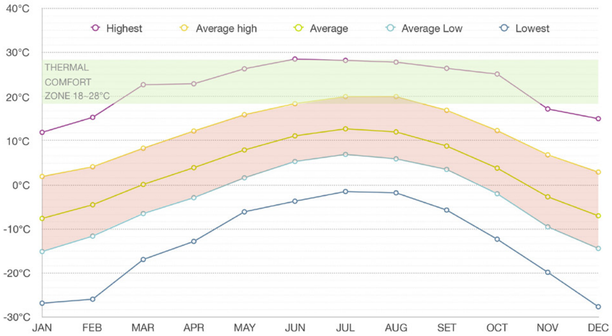

Figure 2 Yushu Temperature (1971-2000)

*lauhingching@gmail.com | Mr. LAU Hing Ching

Xiasi Village School, Sichuan, 2009 August

Dazu Village School, Sichuan, 2010 August

Meishui Village School, Yunnan, 2011 April

I-House Shenzhen, 2011 November

Anzihe Eco-base, Sichuan, 2011 July

Liziping Eco-base, Sichuan, 2012 September

Pudong Eco-base, Shanghai, 2013 February

Baishuihe Eco-base, Sichuan, 2013 March

Mcedo School, Kenya, 2014 September

Village Bank, Xuzhou , 2014 December

Kindergarten, Gansu , 2015 April

Poyang Lake Eco-base, Jiangxi , 2015 June

Figure 3 AIIA Projects (2009-2015)

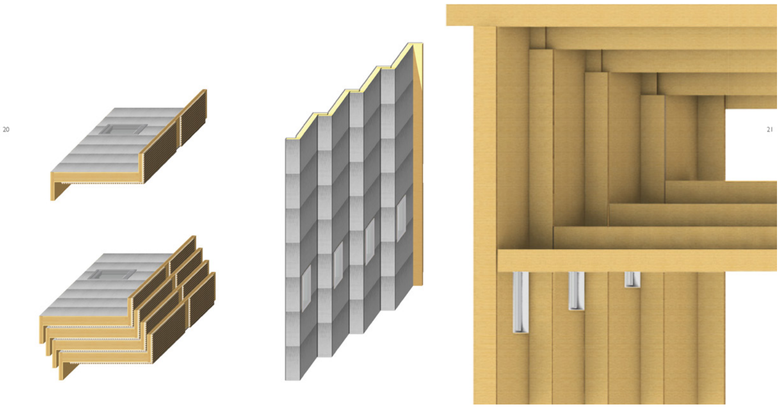

Figure 4 Z-Panel System : Element, Stack, Wall, Floor, Roof, Building

2. Z-PANEL SYSTEM

Large effort was spent on investigating the breaking point of the existing practice of lightweight prefabrication. Based on the previous experience, the research team attempted at a new system which can further enlarge the advantages of lightweight prefabrication: rapid assembling period, high quality control of building, etc., and at the same time reduce the potential weaknesses including labour intensive construction methods, high transportation cost of components, etc. The research team believed it is worth exploring a lightweight prefabricated product for the New Lawuga School project in Yushu.

Through in-depth investigation and researches, the AIIA research team found the answer - Z-shaped panel. The fundamental element of Z-Panel System is large panels with a sectional Z-shape.

2.1 Design Concept

The two "wings" at the long edges entrust the spatial defining panels with the structural possibilities. In the transportation and construction process, the wings help prevent the flat panel from transformation. In the building system, if the panel is placed horizontally as floor or ceiling slabs, the wings become beams overcoming the span; if it is placed vertically as a wall panel the wings would help resist the lateral force.

Besides, Z-shaped panel has a high spatial efficiency in stacking for storage. This is important especially in the case of prefabrication when the logistic takes up a large portion of the budget. The Z-panel can stand by itself, greatly reducing the temporary structures required during construction. When two Z-shaped panels are connected, overlapping the "wings" is an easy connection which gives strong structural performance, and provides excellent air-tightness.

Figure 5 Sectional Perspective

In the later stage, panels with C-shaped and L-shaped sections are also developed.

2.2 Composition

The composition of the Z-shaped panel is based on Structural Insulated Panel (SIP), which is a sandwich composite with foam core (e.g., expanded polystyrene (EPS) or extruded polystyrene (XPS)) in between the sheeting material (plywood, oriented strand board, steel or fibre-cement). SIP has an outstanding performance in both thermal insulation and structural stability. In the New Lawuga School, XPS with plywood on two sides make up the central core of the panels. Other layers of gypsum board, waterproofing membrane, finishing materials such as acoustic panels and metal claddings are incorporated to fulfill the requirement of water/fire-proofing and protection, according to the role of the panel in the building.

2.3 Panel Dimension

The thickness, width and length of each panel is an integrated result responding to multiple disciplines of manufacturing, transportation, construction, structural requirement, thermal performance, and the spatial requirement. For example, the periphery wall panel (Thickness = 150mm) is thicker than the suspended floor panel (90mm) to withstand the exterior environment; the width of the panels is defined by that of the raw plywood panel (1220mm); the length of all panels are limited by 9m for lorry transportation.

3. NEW LAWUGA SCHOOL

A successful application in the harsh natural environment will be a powerful convincing showcase of promoting the system. Using the innovative Z-Panel System, the New Lawuga School was completed in August 2015, and was soon put into operation. Originated from Z-Panel system, the building also incorporates architect's design philosophy and becomes an outstanding architecture in the village.

3.1 Spatial Quality

The New Lawuga School was a two-storey building providing 200 sqm of usable floor area. The simple "Z-Panel" idea allowed complex spaces to be formed within the small tidy building. The stepped peripheries of the walls and roof were the direct visual interpretation of the Z-shaped panels. The school consisted of a central double-height stairway connecting to four classrooms, with an independent storage underneath. Each space was different from each other. This differentiation originated from the space's scale, spatial geometry and orientation. The G/F classrooms had a stepped ceiling getting higher at the East. The 1/F rooms were stepped classrooms, with a dramatic ceiling height at the West. The differentiation was further enhanced by window design, which controlled the view and light condition. Each space had an individual spatial geometry, yet all different spaces were dependent closely with each other. Loop circulation was formed providing a rich and endless spatial experience to the users.

3.2 Openings

The unique spatial identity of each room was enhanced by the opening designs. Large sky windows in the central stairway flooded the space with natural light, creating a reverential atmosphere. There was a series of side windows looking towards the school campus in the G/F classrooms, while in the 1/F classrooms, the side windows faced inwards to the bright central stairway. Besides, small sky windows and large translucent panels at the East could capture the extraordinary landscape outside the classrooms.

3.3 Internal Finishes

Contrasting to the complicated spatial geometry, only two materials were used for the interior finishing: acoustic panel and wood floor plank, both with the warm wood colour. All the doors, window frames, and built-in furniture shared the similar warm and golden tone. The plasticity of the surfaces created a cosy atmosphere for teaching and studying. The pattern of the acoustic panel used in the walls and the ceilings diminished the gaps due to construction. The intervals between the acoustic panels allowed certain degree of bending during installation.

Figure 6 1/F Classroom

3.4 Exterior Finishes

The facades at the South and North, and the roof of buildings were coated with a thin layer of metal cladding. The metal claddings offered robust and lasting protection against water, wind and weather. To explore the materiality, two types of metal were applied: galvanised steel was used in the South elevation and the roof, while stainless steel was used at the North Elevation. The claddings were arranged from the top. As the roof was stepping, alternative pattern was created. The windows were covered with the claddings. The East and West elevation were large pieces of polycarbonate sheet, with dark wooden channels at the back. Thus, a monolithic object shimmering with a vast range of colours and reflections was erected on the plateau.

Figure 7 South-west view of New Lawuga School

3.5 Building Physics

Construction of buildings on this unyielding plateau areas needed to pay special attention to the relationship with the environment. The New Lawuga School was lifted up from the ground to prevent undesirable emission of heat to the subsoil. The massing reduced heat loss from the building shell by having a lower surface to volume ratio. All the periphery panels, floor, wall and roof panels, had a thick insulation layer of 150mm, ensuring low thermal transfer values. All the fenestrations were double-glazed to improve thermal isolation. At the East and West elevations, trombe walls which were made up of wooden L-shaped framework and polycarbonate sheets were installed. Simple operation could allow the trombe walls, which could obtain large quantities of passive-solar energy and create air barrier, to prevent energy exchange, with the external environment. The external polycarbonate sheets, depending on the light situation, could appear anything from deep black, like an abstract black hole, to dazzlingly bright, reflecting the mountains and sky.

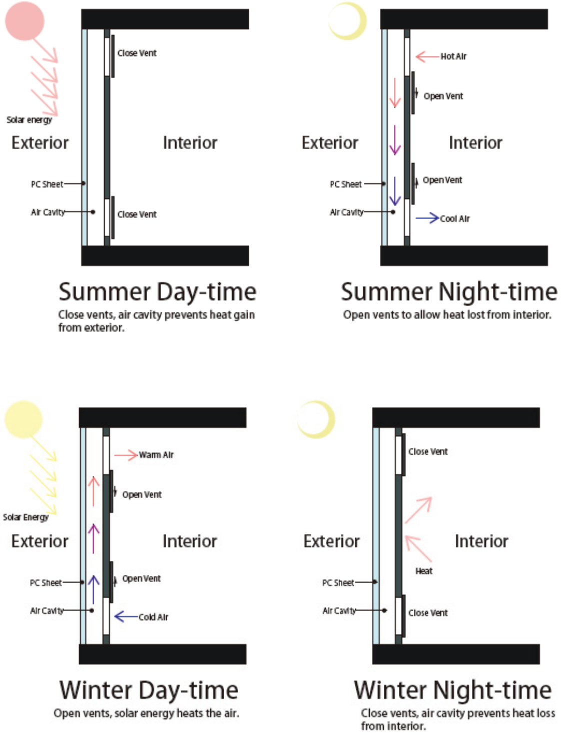

Figure 8 Trombe Wall Concept

3.6 Foundation

The New Lawuga School was only half weight of the same size concrete building. Because of its light weight, ground screw system was introduced for the foundation construction. Comparing to the traditional foundation method such as raft or piles, ground screw system considered both the structural aspect and the construction process, providing a rapid and environmental friendly option. Galvanised steel ground screw, with a diameter of 110mm and length of 2.8m, were pierced into the soil by the powerful driver. The screw pile penetrated through the 1m-thick permafrost layer. The installation of the ground screw was a reversible process, preventing permanent damage to the subsoil.

Figure 9 Installation of Ground Screw

Figure 10 Manufacturing Factory in Chengdu

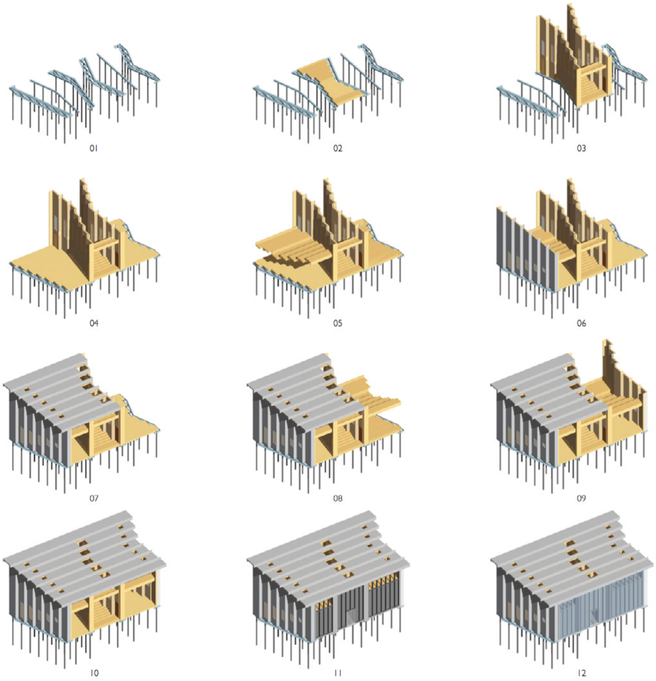

Figure 11 Construction Sequence

4. REALISATION

Solidifying an innovative idea to an authentic building is always an arduous challenge. But founded on the valuable experience of previous practices, and with great effort from different local parties, the New Lawuga School has been operated since 1 September 2015. Erected on the plateau grasslands, it provides a safe and warm learning environment for the remote students, and presents a promising future of the new building prototype.

4.1 Manufacturing

There were two rounds of mock up testing respectively in 2014 June and 2015 January before the formal manufacturing process, to ensure the performance of the Z-shaped Panels. The large-scale manufacturing took place in Chengdu. Manufacturing of all components were carried in three different factories, two wood factories (one responsible for the main panels production, and the other responsible for all other wooden components) and a metal processing factory. The architect had coordinated with different factories for effective manufacturing process.

4.2 Construction

The construction period of New Lawuga School lasted for 2.5 months in Yushu. This was the first time for the design team to work on a project in the province. The 2.5-month period included all preparation works such as searching for co-operating builder and suppliers.

The assembling of all the 80 pieces of panels only took up eight days. The high efficiency was achieved by a simple installation process where the panel is either erected or placed. The efficiency still has room for improvement as this was the first time for the local builder to construct the prefabricated system.

The construction of the building started from the erection of the central core, so that a stable structure could be erected independently. The tolerance due to the construction was shifted to the exterior sides. Following was the installation of the suspended or panels at the South. Temporary steel members were used to support the panels.

Among the assembling process, as the Z-panels were independent objects with strong structural strength, only small amount of temporary support was needed. About 1,500 number of steel members of different length (1.5 m, 3 m, 6 m) were used. Three workers were responsible for the installation of the panels, and other three workers for the temporary supports, hence achieving maximum efficiency of the installation. After all the panels were installed, the trombe wall units and the polycarbonate sheets were furnished.


Figure 12 Construction Process

The erection of the school is a valuable experience to review the design and construction process. The concept of the Z-shaped panel is proven to be effective in shortening the construction period and reducing workers' workload on site, yet some detailed designs could be improved to finalise the application of the system, such as the tolerance control of the panels. The research team has started the reviewing process while the Z-shaped panel is already applied in other project's feasibility stage.

4.3 BIM Application

There were in total 80 pieces of panels to be produced for the project. Although all panels share the same strategy, each panel is unique in terms of size, geometry, opening, finishes, depending on the exact role of the panel in the building system.

The usage of Building Information Modelling (BIM) software (ArchiCAD) increased working efficiency of the architect's team throughout the whole project stage. Fabrication and assembly drawings were directly exported from the 3D model. This allowed realisation of geometrical complicated design by producing precise representation drawings with limited human resources and within short time. Schedules of ordering parts were generated. Cost, weight, and quantity data was monitored throughout the design process. In the following fabrication stage, factories could prepare the raw materials according to the schedules, and manufacture with the detailed drawings. 3D model and the supplementary drawings promoted effective communication between different parties.

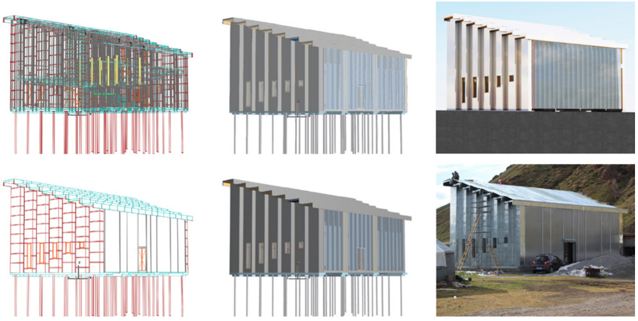
Figure 13 BIM Application

5. EPILOGUE

Prefabrication technology has been the development direction of the building industry for decades. It greatly increases construction efficiency by ensuring building components quality, shortening assembling period required on site, and improving working environment for the workers. Yet the potential of prefabrication should be far more than these.

"Z-Panel System" is the fruitful brainchild through series of research and study. It is an architectural synthesis solution that would be feasible in terms of production, logistic, insulation and assembly, and capable of adopting the special plateau climate. It is simple but effective, and leaves enough flexibility for developing architecture with different scale and programme. The investigation of the innovative technology required the design team to have complete knowledge from manufacturing to assembling, and to work closely with material suppliers and the factories to produce all-round design proposal. The potential and

Figure 14 Children having lesson in New Lawuga School

benefits of the system are shown by the New Lawuga School, which are not only applicable to the remote plateau area, but also in other environment including high-density city.

Comprehensive construction investigation should include not only high-rise buildings, but also small buildings and lightweight structure. A rich ecosystem contains tree, shrubs and herbs. Scientists study stem cells as it could be easily converted to other organs and tissues. The "stem cells" in building industry means system. Among systems, geometric system would particularly influence performance of the material, structure and construction. The pioneers of both architectural, engineering and invention capability include Richard Buckminster Fuller from USA and Frei Otto from Germany. Following the great pioneers, AIIA explored along the direction, and achieved three levels of milestone in New Lawuga School: (i) completion of an exemplary school in Tibetan plateau of 3,900 a.s.l. ; (ii) application of BIM technology as the key design tool; and (iii) invention of the Z-Panel prefabrication system.

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BIOGRAPHY

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ACADEMIA 2ND PRIZE

Carbon Neutral Construction Products Manufactured with Cement and Concrete Wastes

Left:
Ir S.S. LEE
Former Chairman of the CIC

Right:
Prof. POON Chi-sun
Hong Kong Polytechnic University

DEVELOPMENT OF CARBON NEUTRAL CONSTRUCTION PRODUCTS WITH CEMENT AND CONCRETE WASTES BY MINERAL CARBONATION

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Large amounts of concrete wastes, like concrete slurry waste (CSW) from concrete batching plants and recycled concrete aggregates (RCAs) from demolition of concrete structures, are generated in Hong Kong. Towards a closed loop concrete production system for sustainable development, this study aimed to investigate the CO_2 sequestration potential of CSW and its valorisation with fine recycled concrete aggregates (FRCAs) for the production of carbon neutral construction products. The calcium-silicate rich CSW in the fresh state was considered as a cementitious paste to partially replace cement in the concrete mixture as well as a CO_2 capture medium during mineral carbonation. Over 75% of the CO_2 uptake by CSW, FRCAs and their mixture occurred in less than 3-hour of the carbonation experiment, and the CSW was able to sequestrate 110 g CO_2 per kg dry mass after 7 days. After mineral carbonation, the mixture prepared with CSW and FRCAs quickly gained strength in a few hours and suffered lower drying shrinkage. As a consequence, adopting this technology for the production of sustainable construction products would contribute to effective reuse of concrete wastes and to some extent mitigate the industrial greenhouse gas emissions to the atmosphere.

Keywords: concrete slurry waste, CO_2 sequestration, accelerated mineral carbonation, greenhouse gas emission.

1. INTRODUCTION

With global warming due to greenhouse gas (GHG) emissions, zero-carbon and carbon neutral products and developments are nowadays becoming more popular, and some of the initiatives are already entrenched in legislations. In Hong Kong, a target has been set to reduce carbon intensity by 50-60% of the level of 2005 by 2020. The construction sector is the second largest contributor of the carbon footprint in Hong Kong (Mattoon, 2013), and in particular cement, one of the important constituents of concrete, generates more than 5% of the total anthropogenic CO_2 emissions (IEA/WBCSD, 2009).

Moreover, large amounts of concrete wastes, such as recycled concrete aggregates (RCAs) from demolished buildings and concrete slurry waste (CSW) from concrete batching plants, are generated in Hong Kong (Figures 1 and 2). With increasing environmental awareness, more and more ready-mixed concrete producers in Hong Kong have installed fresh concrete waste recycling systems to reclaim aggregates from the over-ordered or rejected concrete so as to reduce the quantity of waste requiring disposal. Cement slurry waste is one of the major end products of such reclaim systems. The quantity of CSW produced is about 0.02 ton per cubic meter produced concrete. (Currently, Hong Kong produces 8,000,000 m^3 ready-mixed concrete per year). For fine recycled concrete aggregates (FRCAs), it is a by-product of the construction and demolition waste recycling process and it accounts for 40% to 70% of the total materials processed at the recycling plant. Although coarse RCAs have potential to be used to replace natural aggregates in concrete and other concrete products, the potential for re-using FRCAs is very limited because it contains a large amount of old cement mortars and has a high water absorption value (Evangelista and de Brito, 2007). As a consequence, options for beneficial reuse of both CSW and FRCAs are needed for sustainable development.

It is known that cement and concrete wastes, containing a high amount of calcium silicate hydrates, calcium hydroxide and other anhydrous cement components, have good carbonation potentials to react with CO_2, leading to the formation of stable solid carbonates to help microstructural densification. Based on this behaviour, an innovative method has been developed to produce carbon neutral construction products incorporating cement and concrete wastes by using waste CO_2 as a curing agent. In this technology, the fresh CSW and FRCAs were considered as the binder and aggregates respectively to manufacture the sustainable concrete products.

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Figure 1 Production of RCAs at a C&D waste recycling plant in Hong Kong

Figure 2 CSW generation at a ready-mixed concrete plant in Hong Kong

2. MATERIALS AND EXPERIMENTAL METHODS

2.1 Materials

Fresh CSWs were randomly collected from ready-mixed concrete plants equipped with the aggregate reclaiming system in 2014. After going through the sedimentation and dewatering stage, the CSW generated was delivered to the laboratory and stored in airtight plastic bags. Since the CSW contained a large amount of waste (moisture content ~ 50%), they were still workable for 3-7 days upon remixing using a mechanical mixer. The average water content in the collected fresh CSWs measured by an oven drying method was about 50% and the maximum particle size of the dried solid particles was 0.15 mm.

FRCAs with the size less than 5.0 mm were collected from a construction waste recycling plant in Hong Kong. The collected FRCAs had a specific density of 2.661g/cm^3, a particle density of 2.075 g/cm^3 and a 24-hour water absorption value of 10.6%. ASTM Type I Portland cement, which had a specific gravity of 3.15 g/cm^3 and a specific surface area of 3960 cm^2/g, was used.

2.2 Mixture proportion and fabrication of blocks

After some trials, the final mix proportion of the designed concrete mixture was 1 CSW: 4 FRCAs: 0.15 OPC by mass. The water content in CSW was sufficient to obtain an acceptable workability of the mix and no additional water was needed. After homogenously mixing all the constituents in a mixer, a uniform amount by mass of the freshly prepared mixture was cast into steel moulds (ø53.5×50 mm and 25×25×285 mm) and then pre-compacted manually using a hammer in three equally distributed layers. A pressure of 30 MPa provided by a hydraulic compression machine was then applied onto the specimens and the maximum load was held for 30s. Once the compaction was completed, all the specimens in cylindrical moulds were demoulded immediately, while the prism specimens were demoulded after 24 hours.

2.3 Accelerated mineral carbonation

In this study, both air curing and accelerated CO_2 curing were employed. Air curing is a commonly used curing method for concrete blocks, in which the specimens are placed in ambient conditions for 28 days. Accelerated mineral carbonation, also named as CO_2 curing, enables quick strength development by taking advantage of the chemical reactions between cement hydration products and CO_2 (Zhan *et al.*, 2013). After demoulding, the specimens for the accelerated mineral carbonation were first placed in a drying chamber with a constant temperature of 25±3°C and relative humidity of 50±5% for 6 hours in order to achieve the optimal moisture condition for carbonation.

As shown in Figure 3, in the laboratory, an airtight steel-cylindrical chamber with a volume of about 100L, controlled under a gas pressure of 0.1 bar, was used for accelerated mineral carbonation. Before CO_2 gas was injected, the chamber was vacuumed to -0.6 bar by a vacuum pump. A commercially sourced CO_2 gas (>99.5% purity) was then injected to the chamber and the chamber pressure was further controlled at 0.1 bar by a gas regulator.

2.4 Measurement of workability of CSWs

The flow table test was used to evaluate the consistence of the collected CSWs in accordance with BS EN 1015-3. The flow value of CSWs was measured immediately after they


Figure 3 Accelerated mineral carbonation equipment


Figure 4 Workability of collected CSW before and after mixing

were delivered to laboratory, and re-tested periodically during the first week of laboratory storage.

2.5 Determination of CO_2 sequestration extent

The theoretical CO_2 sequestration extent of cementitious materials developed by Steinour (Steinour, 1959), based on the stoichiometry and the reactive-oxide content of the concerned materials, was calculated as follows:

$$\%ThCO_2 = 0.785CaO - 0.440CaCO_3 - 0.550SO_3 + 1.091MgO + 1.420Na_2O + 0.935K_2O \quad (1)$$

The initial amount of embodied CO_2 (% $InCO_2$) from carbonates in the pre-carbonated samples and the experimental determined CO_2 sequestration extent in the post-carbonated specimens (% $ExCO_2$) were determined by thermal gravimetric analysis (TGA/DSC, Netzch STA 449C, Jupiter). The samples for TGA were heated continuously in the temperature range from 25°C to 1050°C at a heating rate of 10°C/min in a nitrogen atmosphere with a flow rate of 50mL/min. It has been acknowledged that the mass loss (ΔMCO2) occurred in the temperature range from 550°C to 850°C is mainly due to the release of CO_2 from carbonates (Xuan *et al.*, 2016). Therefore, for the pre-carbonated components and the post-carbonated mixtures, the respective CO_2 percentages in the samples were calculated by the following equation:

$$\%W_{CO_2}(sample) = \frac{\Delta M_{CO_2}}{M_{105^\circ C}} \times 100\% \quad (2)$$

Where, $M_{105^\circ C}$ is the dry mass of the sample;
ΔM_{CO_2} is the mass loss of the sample between 550°C and 850°C;
$\%W_{CO_2}(sample)$ is the percentage of CO_2 uptake by the sample.

2.6 Measurement of compressive strength

The cylindrical specimens with a dimension of ø53.5×50 mm were prepared for the compressive strength testing. For each batch, three specimens were used to obtain the results.

2.7 Measurement of drying shrinkage

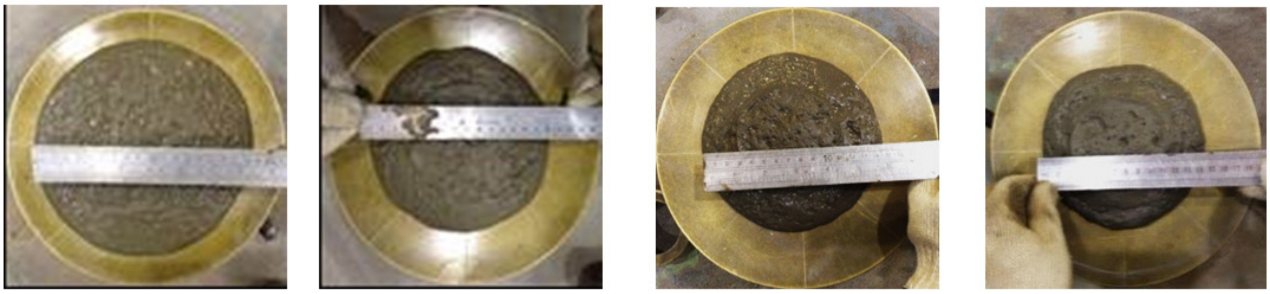
The prism mixture specimens with dimensions of 25×25×285 mm were used for the drying shrinkage measurement. The air-cured specimens after demoulding and the carbonated specimens after different carbonation periods were first placed into a water tank at room temperature for 7 days. The specimens were then transferred to an environmental chamber at a temperature of 25 ±3°C with a relative humidity of 50±5%. The length measurements were then conducted at 1, 3, 7, 14 and 28 days after the initial measurement.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Workability development of CSWs with storage time

The collected CSW before and after mixing in the laboratory mixer is shown in Figure 4. The collected CSW was initially like dewatered pellets (cakes) obtained after the filter press process of the reclaiming system. After mixing in the mechanical mixer, it was observed that they could easily re-gain workability. This was due to its high initial water content.

The workability development of the collected CSW as a function of storage time is shown in Figure 5. With the increase in the storage period, the flow value of CSW appreciably decreased. For the CSW, after 7 days, it became difficult to mix to form a paste and there were more agglomerated particles in the paste. This could be due to hydration of the residual cement in CSW. This hardening behaviour of CSW had been utilised for using them as recycled fine/coarse aggregates in concrete or concrete products (Kou *et al.*, 2012a, Kou *et al.*, 2012b). In this study, the fresh CSW before hardening was evaluated as a binder in new construction products.



On day of generation 7 Days 15 Days 21 Days

Figure 5 Workability of CSW at different storage days

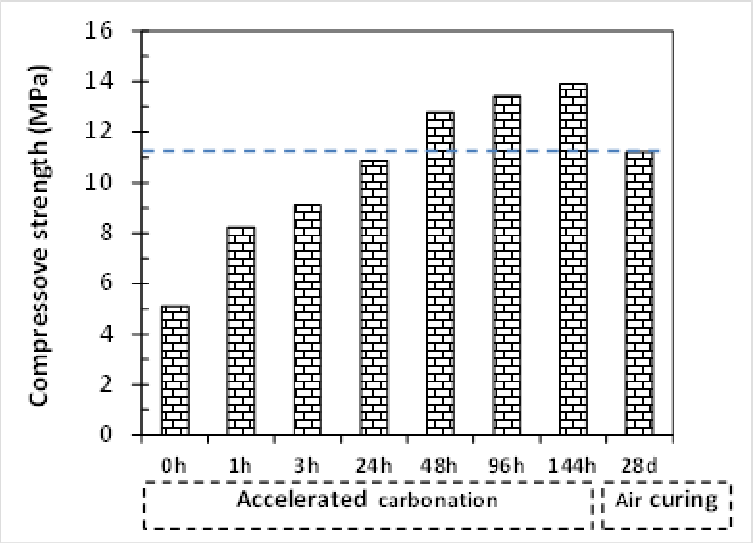


Figure 6 Compressive strength of concrete mixture with CSW and FRCA

It was also found that in ten batches of the collected CSWs, the variation of water to solid content, determined by a 105°C oven drying method, ranged from 0.76 to 1.12. This was mainly due to the variation in the daily settings of the reclaiming system. A lower initial water content in CSW resulted in a faster workability decrease with time. This is consistent with the fact that the water content determined the initial workability and the change of workability with time like a normal cement paste (Mehta and Monteiro, 2006). As a consequence, it is suggested to use the fresh CSW within a few days (< 3days).

3.2 Compressive strength of concrete mixture

The compressive strength of the concrete mixtures prepared with CSW and FRCAs after air curing and accelerated mineral carbonation is shown in Figure 6. The compressive strength of the 3-hour accelerated carbonated specimens was about 80% of those cured in air for 28 days, which demonstrated the ability of the accelerated mineral carbonation to induce rapid strength gains within a few hours.

Extending the accelerated mineral carbonation duration, the compressive strength of the carbonated mixture continued to increase. After 48 hours of accelerated carbonation, the strength exceeded that of the 28 day air cured counterpart. Recently, the adoption of the accelerated carbonation technique to fabricate concrete blocks has already been proposed by some researchers (Zhan *et al.*, 2013, El-Hassan and Shao, 2014). The idea is based on the reactions between CO_2 and the hydration products of cement in concrete: $Ca(OH)_2$, $C_xS_yH_z$ gel and AFt (ettringite)(Morandeau *et al.*, 2014, Kashef-Haghighi, *et al.* 2015). The theoretical calculation indicates that the complete carbonation of a concrete sample could take up 50% of CO_2 by its cement mass. After carbonation, the $CaCO_3$ formed from $Ca(OH)_2$ and $C_xS_yH_z$ gel may increase the solid volume by 11.8% and 23% respectively (Fernandez Bertos *et al.*, 2004, Zhang *et al.*, 2015), which results in an overall reduction in porosity and densifies the whole microstructure. It was demonstrated that by using this technique, cement products may rapidly attain the targeted strength as well as sequestrate a considerable amount of CO_2 (El-Hassan and Shao, 2014).

3.3 CO_2 sequestration of CSW and the mixture

Figure 7 shows the CO_2 uptake rates by the collected CSWs and its mixture as a function of carbonation duration. It can be observed that the CO_2 uptake rate increased with mineral carbonation duration, with over 75% of the experimental CO_2 uptake occurred in the first 3 hours, followed by a more gradual carbonate conversion with

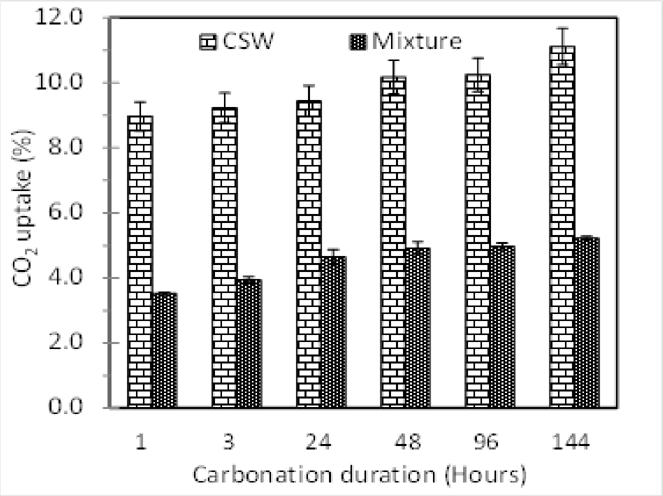


Figure 7 CO_2 uptake of CSW and concrete mixture with carbonation duration

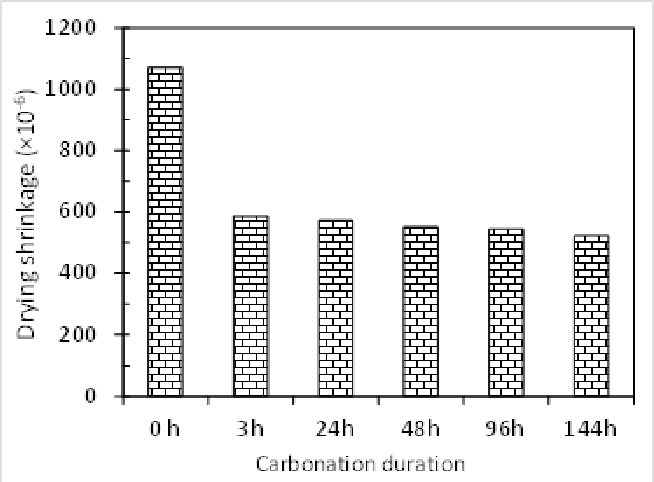


Figure 8 Drying shrinkage of carbonated concrete mixtures at 14 days

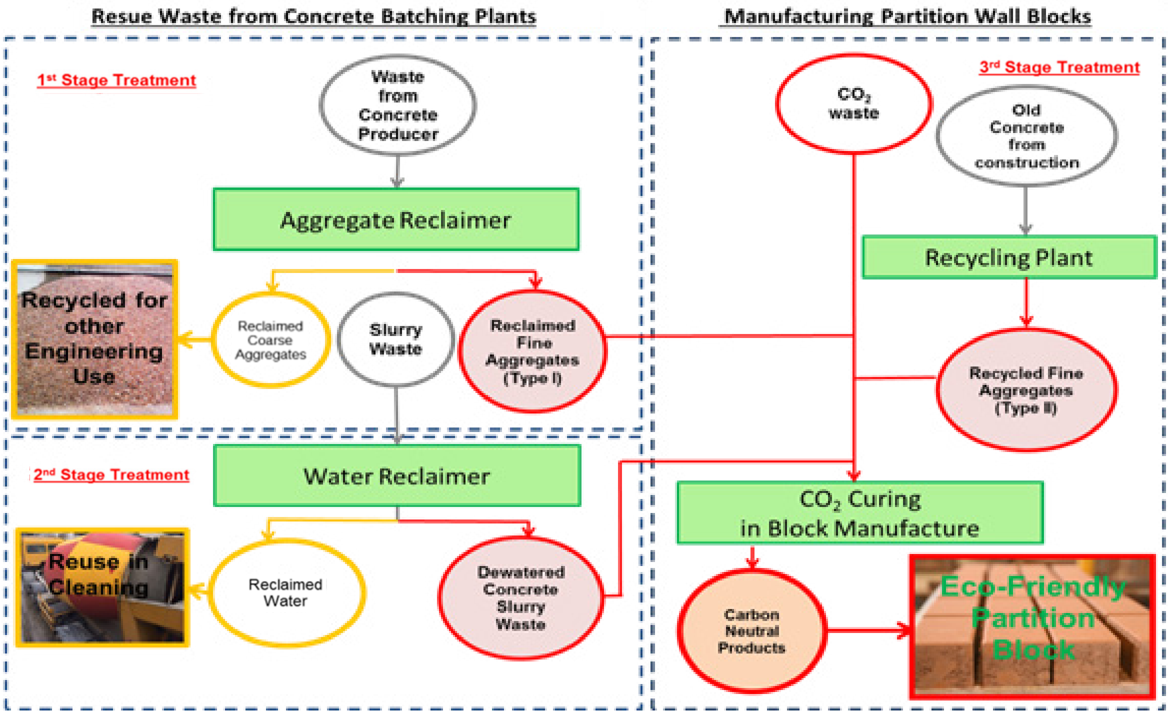


Figure 9 Flowchart of fabrication process of carbon neutral construction products

Figure 10 CO_2 resources from landfills in Hong Kong
(source: EPD) http://www.epd.gov.hk/epd/english/environmentinhk/waste/prob_solutions/msw_lgu.html)

Table 1 Potential benefits of the developed recycling technology for Hong Kong (per annum)

Economic Benefit	**Environmental Benefit**
400,000 ton construction waste reused	12,800 ton waste CO2 captured
38,400 ton cement saved	80,000 m3 saving of disposal site capacity
$20 million saving on waste management cost	Eliminate waste from ready-mixed concrete production

prolonged carbonation duration. After 144 hours of mineral carbonation, the experimental results showed that 110 g CO_2 uptake /kg dry CSW and 52 g CO_2 uptake/kg mixture were achieved by the mineral carbonation reactions. Due to the CO_2 sequestration, the production of the concrete mixture using the developed technique can lower the CO_2 emissions associated with the partition wall blocks production, and it can be regarded as an environmentally sustainable product.

3.4 Drying shrinkage of concrete mixture

The drying shrinkage of concrete mixtures measured at 14 days is shown in Figure 8. Compared to the air cured samples, an obvious decrease (about 50%) in drying shrinkage values of the carbonated samples can be observed. Moreover, prolonging the carbonation duration to more than 3 hours had limited impact on drying shrinkage reduction. This shows using the accelerated mineral carbonation curing scheme, the dimension stability of concrete products can be significantly improved.

3.5 Resources utilisation for waste management

Based on the above laboratory test results, it is proposed that carbon neutral construction products can be fabricated using a process shown in Figure 9. In this process, cement and concrete wastes, including CSW, reclaimed fine aggregate from concrete batching plants and FRCA from C&D waste recycling plants are considered as resources for the production of new concrete products. Furthermore, waste CO_2 sources, for example landfill gas which contains about 50% CO_2 (Figure10), can be utilised for the mineral carbonation process. Previous research have indicated that flue gases with over 10% CO_2 concentration are suitable for use in accelerated carbonation processes of cement based materials (Thiery *et al.*, 2013). If the block manufacturing plants are set up near the CO_2 emission sources, the financial barrier of storing and transporting the CO_2 can be eliminated. The developed technique can contribute to the sustainable development in the construction industry. Some preliminary estimations of the economic and environmental benefits of the developed recycling process are summarised in Table 1.

4. CONCLUSION

This study has demonstrated that by optimising the mineral carbonation technique, concrete wastes like CSW and FRCAs may be regarded as renewable resources (cementitious binder and aggregates), and valorised to produce sustainable construction products which can mitigate carbon dioxide emissions. The additional use of a mineral carbonation technique can help attain rapid strength gains and improve the dimensional stability.

ACKNOWLEDGEMENTS

This work was funded by the Innovation and Technology Support Programme Guangdong-Hong Kong Technology Cooperation Funding Scheme (ITSP-TCFS) and the Hong Kong Polytechnic University (Projects of Strategic Importance). We would also like to thank Gammon Construction Limited for providing the cement slurry waste for the experiment.

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BIOGRAPHY

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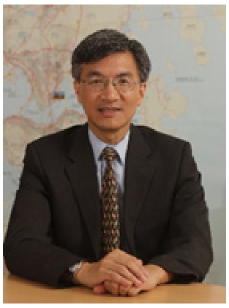

Prof. Chi Sun POON is currently the Chair Professor of Sustainable Construction Materials and Associate Head of the Department of Civil and Environmental Engineering of The Hong Kong Polytechnic University. He specialises in the teaching and research of construction materials and waste management. He pioneered the development of the Eco-block technology for turning wastes into construction materials. He has published over 400 papers in international journals and conferences. Prof. POON is a Fellow of the Hong Kong Institution of Engineers and the Hong Kong Concrete Institute (HKCI) and he is the current president of HKCI.

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YOUNG INNOVATOR (INDUSTRY PRACTITIONERS)

Innovative Use of Polymer Solutions for the Construction of Diaphragm Walls

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Ir Kevin POOLE
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INNOVATIVE USE OF POLYMER SOLUTIONS FOR THE CONSTRUCTION OF DIAPHRAGM WALLS AND BORED PILES IN HONG KONG

Carlos LAM[1,*]

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Bentonite clay slurry is commonly used for the construction of diaphragm walls and bored piles in Hong Kong. However, this material has several disadvantages which make them unsuitable for use in urban construction sites. Polymer fluids are an innovative material that can be used to replace bentonite clay slurry to stabilise loose soils during construction of diaphragm walls and bored piles. This paper briefly discusses the advantages of these fluids. It can be foreseen that the application of polymer fluids in Hong Kong will make the construction of diaphragm walls and foundation piles more efficient and sustainable.

Keywords: polymer solutions, diaphragm wall, excavation.

1. INTRODUCTION

Hong Kong is a city with a high population density. Due to scarcity of land, underground space is an important resource and is essential for the sustainable development of Hong Kong. In many large-scale underground development projects (e.g. basements of high-rise buildings), diaphragm walls are commonly used as retaining walls to support the earth while excavation takes place on the other side. These walls, which could be over 50 m deep, are made of reinforced concrete and are the key components of an underground structure. Traditionally, these walls are formed by excavating a trench filled with bentonite clay slurry (Figure 1) before wet concrete is placed. The clay slurry is used to exert a stabilising pressure on the trench walls to prevent them from collapsing. Due to its useful properties, bentonite clay slurry is also commonly used in Hong Kong for the construction of bored piles and barrettes which are deep foundations.

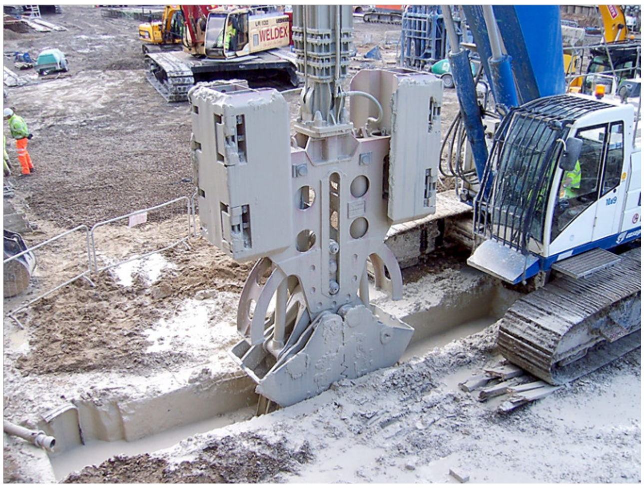

Figure 1 A diaphragm wall trench filled with bentonite clay slurry

2. DISADVANTAGES OF BENTONITE CLAY SLURRY

Despite its widespread use, bentonite clay slurry has several disadvantages:

Bentonite clay is commonly supplied in powder form in 25-kg bags for smaller projects. To mix the powder with water to form slurry, the site operative needs to manually break the bags. This creates a health risk for the operative as the fine powder can become suspended in air during the process. Figure 2 shows an operative wearing a dust mask while breaking a bag of bentonite clay powder. Personal protective equipment should be the last resort in risk control, and it will be ideal to eliminate the risk at the source, such as by using alternative materials that do not pose such risk.

Figure 2 A construction worker wearing a dusk mask when breaking paper bags containing bentonite clay powder

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Figure 3 Bulky site equipment used for storing and cleaning bentonite clay slurry

Figure 4 Bentonite filer cake adhering on the surface of a piece of concrete

Figure 5 Mixing polymer fluids on a construction site

Although bentonite clay slurry is a well-established construction material, it is unsuitable for many urban projects due to the large demand for space to accommodate the slurry-cleaning and storage equipment. In order to recycle the used slurry, it needs to be cleaned to remove any sand and silt particles it picked during excavation. Figure 3 shows the equipment used for storing and cleaning bentonite slurry in a project in Hong Kong. It would be ideal to use alternative stabilising fluids that do not require such bulky equipment for storage and treatment.

At the end of a large-scale project, the unwanted slurry, which could amount to over 10,000 m^3, needs to be disposed off-site. This significantly increases the local traffic and also the demand on landfill sites or marine spoil grounds (Environmental Protection Department, 1994). Therefore, there is a real need for a more environmental friendly fluid that could replace bentonite slurry.

Since bentonite slurry can form a layer of soft material known as filter cake on the surface of the side walls of trenches and bores, the completed walls and piles can have low interface friction with the surrounding soil due to the filter cake in between. Therefore, the presence of a filter cake reduces load-bearing capacities of the walls and piles, and makes them inefficient in transferring loads from the superstructures to the ground. Figure 4 shows a layer of bentonite adhering to the surface of a piece of concrete. The consequence of this is that the walls or piles would have to be made deeper to have the required load-bearing capacity, thereby increasing the construction costs. A stabilising fluid that does not form soft filter cakes on the side walls of trenches and pile bores is thus much desirable.

3. ADVANTAGES OF POLYMER FLUID

Research carried out by the author has shown that polymer fluids can offer many advantages over the conventional bentonite clay slurry for the construction of diaphragm walls and foundation piles, as follows:

- *No health risk*
  Polymer fluids can be mixed by simply adding dry granules into running water. Figure 5 shows the process of mixing polymer fluids on site, where dry polymer granules were being sprinkled to running water. It can be seen that no fine powder became suspended in the air during the process. This eliminates the associated health risk to the workers and thus the need to wear dust masks.

- *Less storage space*
  Typically only 1 kg of polymer granules is required to prepare for 1 m^3 of polymer fluids with sufficient viscosity. In contrast, 50 to 60 kg of bentonite powder are typically required to mix 1 m^3 of bentontie slurry. This difference in material usage means a significant reduction in the demand for storage space on site. For example, in a large-scale project where, say, 10,000 m^3 of stabilising fluid are required. Only 10 tonnes of polymer granules would be needed if polymer fluids are used as the stabilising fluid. In contrast, over 500 tonnes of bentonite powder would be required if bentonite slurry is used.

- *Smaller site footprint*
  Polymer fluids do not require bulky equipment for cleaning due to their self-cleaning properties.

- *More environmental friendly*
  Polymer fluids can be used near environmentally sensitive areas e.g. rivers, whereas bentonite clay slurry, if discharged into the marine environment, can suffocate the marine species (e.g. by clogging the gills of fish). Unfortunately, dumping unwanted bentonite slurry into marine spoil grounds is currently a common practice in Hong Kong.

- *Less construction waste*
  At the end of a project used polymer solutions can be treated on site by adding bleach to reduce the viscosity. The treated fluid can be safely discharged into the local sewers with the permission of the relevant authority. This advantage eliminates the need to transport used slurry to landfill sites or marine spoil grounds.

- *Better finished products*
  Unlike bentonite clay slurry, polymer fluids do not form a layer of soft filter cake on the side walls of trenches and pile bores (Lam *et al.*, 2014). Therefore, the completed diaphragm walls and piles have higher interface friction with the surrounding soil.

A full discussion of the advantages of polymer fluids over bentonite clay slurry can be found in Jefferis and Lam (2013, 2016).

4. CONCLUSIONS

Due to the above environmental and operational benefits, polymer stabilising fluids have the potential to revolutionise the way diaphragm walls and bored piles are constructed in Hong Kong, where the demand for underground space continues to increase. The improvements to the construction process and the environment will improve work efficiency and create better final products, while at the same time impose less pressure on the environment. Together, these benefits will lead to lower construction costs and a more sustainable industry.

ACKNOWLEDGEMENTS

The Author would like to thank Professor Stephan Jefferis for his long-term collaboration in the study of polymer fluids for geotechnical engineering applications.

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BIOGRAPHY

Ir Dr. Carlos LAM is a Geotechnical Engineer of the Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong SAR Government. Formerly a Lecturer in Geotechnical Engineering at The University of Manchester, he has been researching the use of polymer fluids for deep excavations since 2007. He currently sits on the Editorial Advisory Panel for the journal Proceedings of the Institution of Civil Engineers - Geotechnical Engineering. He received the Fugro Prize from the Hong Kong Institution of Engineers (HKIE) Geotechnical Division and the Construction Industry Council (CIC) Innovation Award (Young Innovator for Local Industry Practitioners) in 2015.

YOUNG INNOVATOR (ACADEMIA)

i-Core: Giving Construction a "Heart"

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i-CORE: TOWARDS A CUSTOMISABLE SMART CONSTRUCTION SYSTEM FOR HONG KONG

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Construction leaders in Hong Kong continually endeavor to find innovative solutions to meet the increasingly higher demands of today's construction industry, including building methods that are better, faster, cheaper, safer, greener, and ultimately, more productive. Leading construction companies and research institutes are calling for smart construction, which can be perceived as an overarching term incorporating smart technologies and systems such as automation, robotics, Building Information Modelling (BIM), Virtual Design and Construction (VDC), Internet of Things (IoTs), and Industry 4.0, with a view to improving construction productivity. By extending previous research on smart construction objects (SCOs), the aim of this study is to develop *i-Core*, a standalone, programmable, and extendable integrated chip, with a customisable smart construction system that can be readily implemented in the Hong Kong construction industry. Equipped with *i-Core*, these 'static' construction resources are now capable of sensing, computing, communicating, and taking actions without necessarily involving humans in the loop. An i-Core prototype with the customisable smart system has been developed and piloted in a construction project and is to be scaled up to other construction projects in Hong Kong. *i-Core* can be further applied to, inter alia, critical scenarios such as safety management, construction procedure guiding, and facilities management. *i-Core* gives a 'heart' to construction; it is the 'CPU' of smart construction.

Keywords: i-Core, Smart Construction Objects (SCOs), customisability, construction.

1. INTRODUCTION

Construction is a pillar industry of most economies in the world, contributing to the development of housing, roads, bridges, skyscrapers, and the like, which are instrumental in influencing economic activities, human health, and social behaviour as well as cultural identity and civic pride (Pearce, 2003). Construction contributes around 10% of the Gross Domestic Product (GDP) of the world's major economies. The industry also provides a large number of jobs. For example, around 45 million people in China are employed in construction activities, 6.4 million in the USA, and 12.3 million in the European Union (Lu *et al*., 2015). In Hong Kong, the construction industry accounts for about 4% of the GDP and offers 7.7% of the total employment opportunities, with a consistent upward tendency for the past eight years (C&SD, 2014).

Given its importance, the construction industry's productivity is the mantra that is often chanted by the general public, government, administrators, companies, and other stakeholders. 'The story of productivity, the ratio of output to input, is at heart the record of man's effort to raise himself from poverty' (Kendrick, 1961). Enhancing construction productivity, in layman's language, requires us to build better, faster, and cheaper. Nowadays, construction productivity cannot be achieved at the cost of the environment and the occupational health and safety (OHS) of workers; the dimensions of building greener and safer have therefore to be added. However, many existing construction practices are not amenable to productivity enhancement, and in some cases actually undermine construction productivity. Consider the following construction scenarios:

1. Logistic and supply chain management (LSCM). Construction LSCM is often critical to achieving project management objectives. In practice, construction LSCM is very complicated, involving multiple parties in the processes of production, warehousing, transportation, temporary storage in multiple transfer depots, and finally, on-site usage. It is even more challenging in Hong Kong as the sources of materials are geographically dispersed, leading to a prolonged process. In addition, construction sites are often confined spaces in which the placement of materials and machinery must be very carefully planned. It is not uncommon to see high costs and

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serious delays resulting from a shortage of materials, or when an on-site warehouse runs out of space due to an overly stockpiled inventory. A 'just-in-time' (JIT) LSCM system is compellingly desired;

2. On-site operations. Delicate workflow on-site, such as assembly of prefabricated components or cooperation between different construction plants, needs to be properly guided. At every transition point, a redirection of the workflow based on information from sensors or human input should be provided. Prefabricated components may guide assembly process operators to locate the precise assembly location and to avoid possible clashes. Advanced machines and plants may exchange information and work status by pulling information from each other, and then cooperate by establishing a connection;
3. Construction OHS management. In such a 3D (dangerous, dirty, and demanding) industry, there are numerous hazards on a construction site, lack of awareness of which can cause serious and even fatal accidents, such as falling from height or being hit by moving objects. Noise, vibration, and heat stress can also have serious effects upon the health of construction site workers. Construction OHS management is thus a topic that has long been the concern of administrators, researchers, and practitioners in Hong Kong. Hazards need to be closely monitored and, whenever possible, actions have to be taken autonomously before any harm is caused to construction personnel, who may not respond swiftly enough to emergent hazards.

The construction industry is calling for changes. A series of influential construction industry reports such as the Latham Report (1994), the Egan Report (1998), and the Tang Report (2001), have been published to elucidate some of the deep-rooted problems in construction, e.g. adversarial attitude, fragmentation, discontinuity, and labor shortage. Technical and managerial innovations have been needed for solving these problems at an industry level (Ellmann, 2008). New construction management technologies and concepts, particularly smart construction, relating to sensing technologies, Building Information Modelling (BIM), Internet of Things (IoT) have emerged against this background.

The construction industry shall be more intelligent through the adoption of technologies and innovations. The tenet underpinning this thread of research is that human beings, with their intelligence and cognitive abilities, are central decision-makers; in the construction process, determining the use of construction resources such as materials and machinery. In this people-centric decision-making model, it must also be acknowledged that human beings are not infallible when it comes to processing information and making informed decisions (Reason, 2000). In this context, human intelligence shows deficiencies (such as being slower and more error-prone) when compared with artificial intelligence (AI) (Sterman, 1989). To meet the even-heightened demand of information management for future construction, smarter technologies or even decision-making models that deviate from traditional people centric ones could be reasonably envisaged. Ideally, the construction resources (e.g. materials, precast components and machinery) should be made 'smart' by augmenting them with ubiquitous smartness including sensing, processing and communication abilities so as to enhance information management for construction. *i-Core* is developed to provide this smartness.

2. THEORY/CALCULATION

2.1 Ubiquitous computing and smart objects

The trend to implant smartness to everyday objects originates from the concept of 'ubiquitous computing', which was first put forward in the Computer Science Laboratory (CSL) of the Xerox Palo Alto Research Center (PARC) in early 1988. The idea of ubiquitous computing is to shift the paradigm of 'one person-one desktop computer' to a new form where computers are spread ubiquitously and invisibly into the everyday objects of our lives (Weiser *et al.*, 1999). Under this rationale, these everyday objects can acquire the ability of computer to process and communicate while keeping their original appearance and functions. Therefore, these objects are not necessary to comprise a desktop or laptop as a component, while they could be augmented with the functions of computers. The profound influence of ubiquitous computing paradigm is firstly demonstrated in the manufacturing industry.

As a direct consequence of ubiquitous computing rationale, one technology trend in manufacturing industry emerged with the concept of 'computer-augmented artifacts' proposed by Beigl *et al.* (2001) in their Mediacups project, where non-digital smart objects were first introduced. Smart objects are distinct from non-digital everyday artifacts. The latter were defined as 'a non-computational physical entity with established purpose, appearance and use in everyday experience' by Beigl *et al.* (2001). Smart objects emerge with the purpose to provide added-values of information processing and exchanging with everyday object while its original appearance and functions will not be restricted or compromised (Beigl *et al.*, 2001).The concepts of ubiquitous computing and smart objects have been discussed in the context of various industries such as manufacturing (Huang *et al.*, 2008), transportation (Fuchs *et al.*, 2007) and medical applications (Cheng *et al.*,2008).

2.2 From SCO to i-Core

In responding to the call for smart construction in Hong Kong, Niu *et al.* (2015) developed smart construction objects (SCOs), which are 'construction resources (e.g. machinery, tools, device, materials, components, and even temporary or permanent structures) that are made smart by augmenting them with sensing, processing and communication abilities so that they have autonomy and awareness, and can interact with the vicinity to enable better decision-making'. In addition to the geometric, non-geometric, and semantic information they carry, SCOs have three 'smart' properties including awareness, communicativeness and autonomy (Figure 1). Whilst these SCOs are still providing decision-making information to human decision-makers, what makes them different from conventional construction objects is that they can communicate with each other directly. In doing so, some routine or clearly rule -based decisions can be made by SCOs autonomously without necessarily involving human decision-makers in the loop.

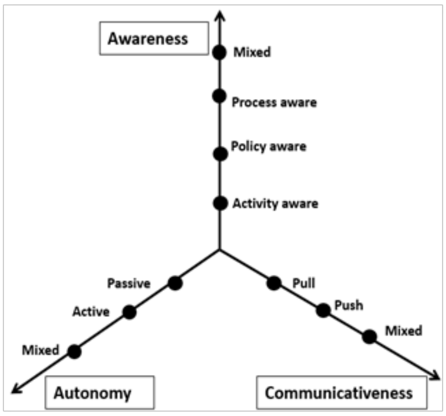

Figure 1 Three core properties of SCOs (Niu *et al.*, 2015)

There are numerous construction scenarios, on-site and off-site, requiring the augmented capabilities of sensing, processing, computing, networking, and reacting to alleviate human beings' difficulty in decision-making. The applications of SCOs and their smart properties are identified in the above construction scenarios that explore the great potentials of SCOs in improving construction productivity, particularly when they are connected with BIM, IoT, and robotics.

However, it is particularly challenging to customise SCOs, which are developed from a generic decision-making scenario, into real-life construction practices, which are often procedure-specific, project-specific, and company-specific. Therefore, *i-Core* is developed to innovatively encapsulate the smartness. *i-Core* denotes a standalone, programmable, and extendable integrated chip that can be implanted to construction machinery, devices, and materials. Similar to a Central Processing Unit (CPU) of a computer, *i-Core* turns static construction components and plants into SCOs, and makes smart construction possible. Various modules can be augmented to *i-Core* to perform different functions in order to meet the changing needs on construction sites(Figure 2).

3. MATERIAL AND METHODS

The development of *i-Core*, a circuit chip in the size no more than a credit card, is the first major step towards the customisable smart construction system. To enable the core chip to achieve smart properties, multiple sensing, communicating and calculating modules would be integrated in order to assist various construction operations. The key modules and some application scenarios are discussed as follows.

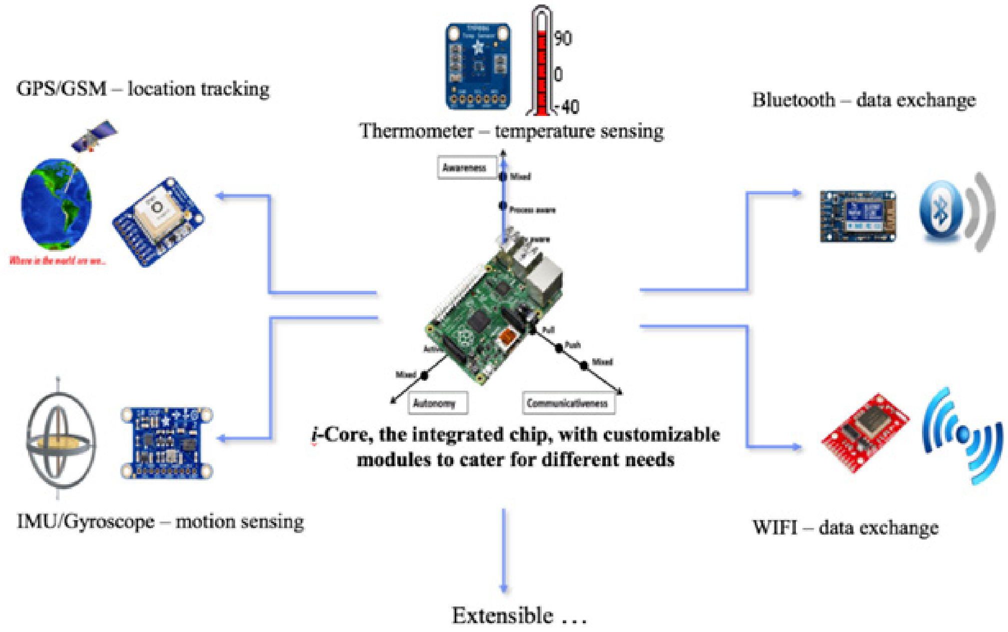

Figure 2 *i-Core* with customisable modules

3.1 *The digitised 3D site*

Establishing a digitised 3D site lays the foundation for tracking and managing the site in a smart construction system. The purpose of digitising the site is to assign each location within the site a unique trixial (x, y, z) coordinate (Figure 3). The x-axis and y-axis form the plane that is parallel to the ground, within which they are perpendicular to each other. The z-axis is parallel to the direction of gravity, which is perpendicular to the X-Y plane. Together, the x-axis, y-axis and z-axis form a 3D cubic grid to contain the whole site and buildings to be erected on it. Therefore, anywhere on site, including temporary storage areas, vehicle parking areas and, construction areas, can be located by corresponding coordinates. Digitising the whole construction site area is fundamental for *i-Core*s to achieve location awareness. The coordinate system serves as the standard of site location information. After *i-Core*s sense their real-time location within the site, the information will be compiled into a (x, y, z) format. When *i-Core*s need to communicate the location information between each other or update the information back to database, it is also conveyed in the (x, y, z) format. The establishment of the digitised 3D site is based on the site plans. The z-axis is set with reference to the elevation plan, while the x-axis and y-axis are set on the site layout plan. Since the location tracking and route calculation are based on relative displacement, the base point (0, 0, 0) can be set at the centre or any angle cubic grid. The digitisation of the site can be linked with the BIM, so that each object in the model carries a matching (x', y', z') value.

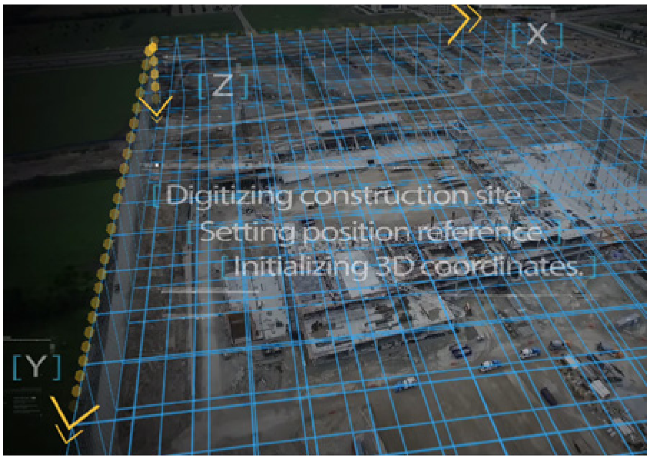

Figure 3 Generating the 3D coordinates system of the construction site

3.2 *Location tracking module*

Location tracing represents a general and fundamental issue that can be seen in many areas such as logistic and supply chain, geography, indoor location, etc. It is also applicable in smart construction. The awareness to sense real-time location is achieved by a location tracking module in *i-Core*. Global Positioning System (GPS) has been widely used in navigation and surveying applications due to its capability to provide a 24-hour worldwide positioning service at a relatively low cost. Relying on satellite signals, the accuracy of GPS has been made possible in a 10-meter level of change (Ochieng and Sauer, 2002). However, GPS may suffer from signal masking and multipath errors in areas shielded by dense buildings or trees (Lu *et al.*, 2007). Hong Kong Island is a typical city canyon area where only around 50% of the test area was receptive to adequate GPS signals in the study by Lu *et al.* (2007). Unlike GPS that relies on satellite for positioning, an inertial measurement unit (IMU) is self-contained and requires no external motion signals for positioning. The IMU is reliable and stable while navigating under conditions of external disturbance. It consists of gyroscope to sense angular rate, accelerometer to sense acceleration and other sensors such as the magnetic sensor so that separate sensor data could be fused into a single optimum estimation (Madgwick *et al.*, 2011). However, with the increase of tracking time and distance, the IMU will suffer from a drifting problem by integration (Huang *et al.*, 2010; Lu *et al.*, 2007). Thus IMU is usually used with other sensors, such as the optical navigation sensor (Hyun *et al.*, 2009), for navigation and positioning purposes. Further improvement on the accuracy of positioning can be achieved by removing the actual biases of accelerometers, magnetometers and gyroscopes.

3.3 *Sensors and microcontroller*

Various sensors can be integrated into *i-Core* chips based on requirements. In other words, *i-Core* is highly flexible to cater for different needs by the construction industry. An important kind of sensor is for location tracking and positioning, which will be introduced in the location-tracking module. *i-Core* is also highly extensible with other kinds of sensors. The microcontroller is vitally important for realising autonomous control. Microcontrollers are widely adopted in autonomous robot controls (Caprari *et al.*, 1998; Crespi *et al.*, 2005). Acting like the 'brain' in an *i-Core* chip, the microcontroller centrally manages the sensors, communicating devices, and the actuators. Data generated is compiled and interpreted by the microcontroller before communication.

3.4 *Communication module*

A communication module in the smart unit achieves ad-hoc communicativeness between *i-Core* enabled components. Compared to other wireless communication technology, Bluetooth is preferred because low-energy Bluetooth could perform lower power consumption (Gomez *et al.*, 2012). It usually takes no less than one month for prefabricated components to be manufactured, delivered and installed on-site. In the Hong Kong-Shenzhen cross-border cooperation for prefabrication construction, the transportation of prefabricated components may take a long time. Most wireless connection modules such as

Wi-Fi modules may largely consume the battery before on-site operation. Comparatively, the low-power Bluetooth may support smart prefabricated components for up to six months. Besides, the Bluetooth wireless module provides a low-cost way for information exchange among mobile devices and provides connectivity to the Internet (Bisdikian, 2001). It enables every object with *i-Core* to be connected by servers or handheld devices. The Global System for Mobile Communication (GSM) module is also capable of data transmission, especially for pushing data to the cloud database. On developing the GSM module, remote two-way communications can be positively expected.

4. RESULTS

The development of *i-Core* is in parallel with practical testing in construction projects. With the strong support from the client and the main contractor, the research idea is realised in a public housing construction project in Hong Kong, which involves five high-rise residential towers and one commercial centre. Before customising the first prototype of *i-Core*, non-participant observation and interviews have been conducted with managers, foremen, and workers to capture their needs. Much effort has been paid to the development of the system, which incorpoarates an *i-Core* prototype linking database, BIM, and Google Map in the user interface.

The *i-Core* prototype has been developed based on an Arduino UNO chip where the smart properties are programmed using C/C++. In the prototype, a GPS module, a global system for mobile (GSM) module, and battery supply are integrated to the Arduino UNO chip (Figure 4). The chip with connected modules is designed in a black box, which could be mounted to machines or components. Besides, each *i-Core* is assigned with a unique identification code, associated with basic design parameters in the system database. To present the data captured and sent back by *i-Core*, the system user interface has been developed on a cloud basis. By receiving the real-time data by *i-Cores*, its locations and delivery status could be visualised (Figure 5) in the system user interface so as to facilitate monitoring and management during the construction phase.

5. DISCUSSION

i-Core with the customisable smart construction system represents an immense opportunity to improve the global construction industry. It could significantly enhance the power of BIM by bridging the information gap between the 'as-built' situation and the building information model. Given the smart properties of *i-Cores* to connect and communicate with each other, they also become the basic components in forming the IoT in the construction industry. With *i-Cores* continuously sensing, logging, and sharing real-time information with each other, the network made up of *i-Cores* can be maintained in an active status, so as to interpret their local situ¬ation, carry chunks of application logic, act on their own, intercommu¬nicate with each other, and exchange information with people. Moreover, from a panoramic view, the development of *i-Core* with the customisable smart construction system could contribute to the Hong Kong construction industry in the following aspects:

5.1 Customisability

With flexible combinations of smart modules and programs, each *i-Core* is highly configurable to suit the expected functions of different construction trades. Taking the information needed by different stakeholders into consideration, the customisable *i-Cores* could cater for needs under various construction conditions. During the testing, practitioners proactively request to customise *i-Core* for their current needs, such as OHS monitoring (Figure 6), remote control of the site office battery supply; and motion sensing of the construction machines to verify the productivity for construction planning. It is of interest from both the academic and industry spheres

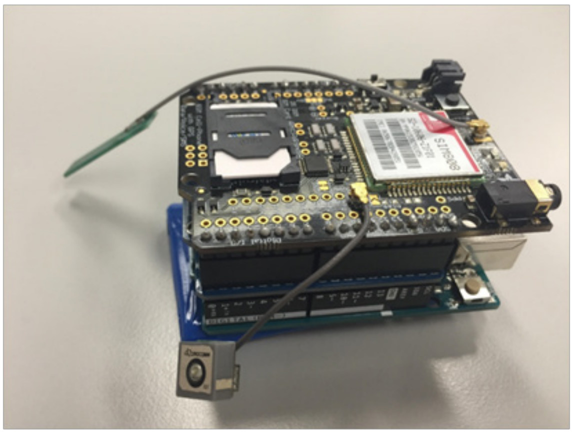

Figure 4 The *i-Core* prototype

Figure 5 Visualisations of the construction logistics

Figure 6 Proposed application of *i-Core* for OHS condition monitoring

to investigate the applications of SCOs in supporting construction management in other scenarios, *inter alia*, safety management, construction process guidance, and facility management.

5.2 Increasing productivity and alleviating labour shortage

With accurate positioning, real-time information updates, and some autonomous action-takings by SCOs, traceability and visibility of construction LSCM can be greatly enhanced, and human errors can also considerably be reduced. The role of people is largely transformed from conducting repetitive labour work to managing SCOs, which can significantly increase the construction productivity in Hong Kong.

5.3 Uplifting the industry's image

The construction industry is wrongly perceived as being low-tech, whereas it is actually as hi-tech as any other industry. The system developed in this project will shed light on the promising future of smart construction, where the construction works could be carried out in a modernised and digitalised way. An improved image could attract youngsters to join the construction industry.

6. CONCLUSIONS

We use our wisdom, entrepreneurship, technologies, sweat, and even life to invent, operate, and optimise myriads machinery, devices, and materials to develop the built environment, which is instrumental in influencing human health and social behavior as well as cultural identity and civic pride. However, the machinery and materials are static, passive, and inert. What if we empower them by implanting them with a 'heart' so that they can also perform arithmetic, logical, control and input/output operations in construction? It is against this backdrop that *i-Core* is initiated as a groundbreaking innovation leading us to the future generation of construction.

i-Core is a standalone, programmable, and extendable electronic circuitry that can be implanted to construction machinery, devices, and materials to make them 'smart', i.e. they have the capabilities of awareness, communicativeness, and autonomy. Equipped with *i-Core*, these 'static' construction resources can be capable of sensing, computing, communicating, and taking action without necessarily involving humans in the loop. In this study, the first prototype of *i-Core* with the customisable smart construction system has been developed and tested in the practical construction projects to alleviate different problems existing in construction.

Nevertheless, it is acknowledged that there are challenges and hurdles on the way to fully operate the system including the conservative mind of construction practitioners and the industry's backwardness to embrace new technologies without instant promising benefits. Future studies are thus recommended to find empirical evidence to quantify the costs and benefits of the customisable smart system. With the feedback from the industry, the canonical system based on *i-Core*s should be customised and scaled up to other construction scenarios that require better decision-making.

ACKNOWLEDGEMENTS

The authors would like to thank Hong Kong Housing Authority and the dedicated practitioners at Gammon Construction Limited, including Gilbert TSENG, Kenneth MO, Alan MO, and Ka Lok WONG for their enduring support of this research.

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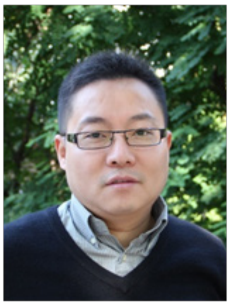

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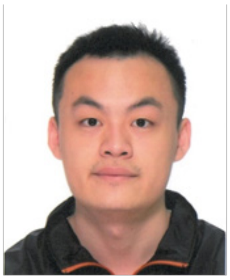

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