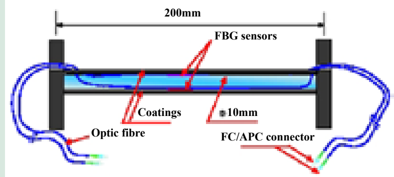
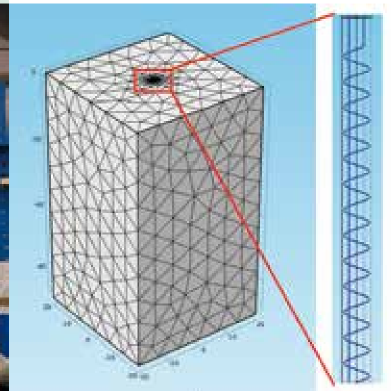
Outcomes of a Collaborative Research Programme with the Construction Industry Part II





MARCH 2016

THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

FACULTY OF CONSTRUCTION AND ENVIRONMENT
建設及環境學院

CONTENTS

Foreword

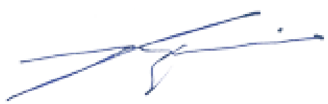
This plain language Executive Summary Report, intended for Construction industry Leaders, has been written to provide a measure of feedback to the Industry on the use of its money. Part of the costs of the research programme reported upon here was provided by Hong Kong construction industry firms, indirectly, via the Construction Industry Institute-Hong Kong (CII-HK).

Launched in 2009, the CII-HK/PolyU Research Fund was established to support 25 research projects of direct relevance to industry. The first 11 of these projects finished in 2014 and were reported in Part I of this document, published in March 2015. The 8 projects which finished during 2015, are reported below in this Part II of the document. The six projects finishing during 2016 will be the subject of Part III of this report to appear in 2017.

The impetus to create the Fund derived from a CII-HK closing down donation to HKPU of HK$4million, to which the Faculty added a further HK$4million.

The 8 projects, below, are diverse in nature covering a) the retrofitting of damaged structures, including the likely required strengthening of structures to comply with coming earthquake resistance provisions and b) environmental sustainability projects concerned with Indoor air quality, making panels from wastes and heat pumps where the heat transfer fluid tubes are cast into the concrete of bored foundation piles. There is also a site management project concerned with the 'real time' tracking of the movements of objects, including personnel, on site.

I hope this report will play its part in stimulating the industry to continue to work with us. The Faculty itself and RISUD (The University's Research Institute in Sustainable Urban Development) are ever ready to collaborate directly with industry partners whenever possible.



Ir Professor You-Lin Xu
Dean
Faculty of Construction and Environment

March 2016

Introduction to the Research Programme

Background

In the year 2009, the Faculty of Construction and Land Use (now Faculty of Construction and Environment, FCE) created a Research Fund entitled the 'Construction Industry Institute (Hong Kong)/PolyU Innovation Fund' shortened to CII-HK/PolyU Innovation Fund. The purpose of the Fund was to encourage collaboration in research and innovation between the Construction Industry and the Faculty.

The Fund was half provided by Faculty research money and half by a closing down donation from CII-HK, a body which existed to promote university/ industry research collaboration, inspired by the 2001 Construction Industry Review Committee Report's recommendation to that end. On the establishment of the CIC, however, (Construction Industry Council) with its own mechanisms for funding collaborative research, the role of CII-HK became redundant and its remaining funds were distributed amongst those universities in Hong Kong which undertook construction research. The Hong Kong Polytechnic University received HK$4million, to which was added a further HK$4million by FCE, as above, making a total Fund of HK$8million.


Ir Professor JG Teng

The decision was made that an individual research project could receive a maximum of HK$300,000 from the Fund. Projects were to be of 2 years duration.


Ir Professor JM Ko

The Research Programme Reported Here

The 8 projects reported below, belong to the second batch funded.The first batch of 11 appeared in Part I of this report published in March 2015. The Fund's contribution to these 8 projects was HK$2.4million.

The projects are quite varied in nature. 4 relate to the field of environmental sustainability, 3 relate to structural behaviour in service and the repair of damaged structures and one project, quite different, is a study of the tracking in 'real time' of the movements on site of items of equipment and personnel. All projects fall within the University's RISUD (Research Institute of Sustainable Urban Development) range of interests and expertise.

The projects are strongly linked to practical application, a cornerstone policy of the University.

The Purpose of this Report

The report is written specifically for Construction Industry Leaders, to feedback on the use made of the money that the construction industry provided for this programme. Six projects, in the third batch, are not yet completed and will be reported next year in Part III.

The report is written in plain language, largely devoid, hopefully, of technical terms which are not commonly understood by persons generally familiar with the construction industry. Each project is allotted two pages only, in providing what is essentially an outline summary. Appendix 2 gives references to already published papers in case there are some who wish to follow up any project in more depth. Most projects, however, finished only recently so the publications list is very much in embryo form. The Principal Investigator should be contacted for any further information if necessary.

Dr J.G. Dai (Project 1)

Dr J.G. Dai
Associate Professor
Department of Civil & Environmental Engineering

To strengthen fire damaged concrete, a ferrocement 'skin' is usually applied. A superior composite skin was developed and tested in this project, consisting of a basaltic textile (non corrosive) to replace the wire mesh and a fibre reinforced cementitious compound to replace the usual cement mortar/shotcrete matrix. This compound and basaltic mesh composite skin can improve the performance of repaired elements by 70-200%.

Dr Dai is a specialist and active researcher in the field of fibre reinforced polymer engineering and construction, including questions of durability in hostile marine environments and advanced composites in structural engineering. He is an active executive member of the International Institute for FRP and Chairman of the design committee of the Asian Concrete Federation.

Professor Wu Chen (Project 2)

Professor Wu Chen
Associate Head & Professor
Department of Land Surveying & Geo-Informatics

This project successfully developed an economical, even cheap, enhanced wireless based system and special software, enabling the locations of objects and persons on site to be tracked in real time. Accuracy is to within 0.5m, precise enough for site management purposes. Current available systems are either too expensive or rely on inertia based navigation systems. The latter become progressively less accurate over time as the errors accumulate with successive moves.

Professor Chen's research interests lie within the advanced technology world of positioning and navigation systems, including kinematic GPS study, GPS receiver software, personal navigation systems and wireless sensor networking. He also spent 8 years in the UK before coming to Hong Kong in the year 2000, working on GNSS, the European equivalent to GPS.

Professor Shun-cheng Lee (Project 3)

Professor Shun-cheng Lee
Professor
Department of Civil &
Environmental Engineering

Indoor air conditions are often very severe for the workers involved in building renovation due to excessive dust and VOC chemicals associated with paints. This project found that exposure to harmful fine dust particles can be 5 times worse than the relevant US standard. VOCs emissions are 27 times worse. Renovation workers need to properly protect themselves, with masks and ventilation where possible and prevent pollution from spreading by confining it to the area under repair.

Professor Lee is an air pollution specialist interested particularly in toxic air modelling and emissions source characterization. He also specializes in risk assessment research, including, for example, indoors exposure to volatile organic compounds. He made a China wide study of the prevalence of carbonaceous aerosols in many major cities. In 2012 he was honoured with the State Natural Science Award of the PRC (second class).

Dr Eddie S.S. Lam (Project 4)

Dr Eddie S.S. Lam
Associate Professor
Department of Civil &
Environmental Engineering

Hong Kong will shortly design buildings with the appropriate degree of earthquake resistance, as is normal in the neighbouring Guangdong province. Many buildings will require some retrofitted strengthening. Along with Freyssinet Ltd, the project measured the increase in column confinement performance of two column 'jacket' designs, consisting of composites of steel wire mesh and dry sprayed shotcrete.

Dr Lam is a reinforced concrete specialist particularly knowledgeable in the field of repair and strengthening. Earthquake engineering links in naturally as another specialist interest. He serves the community on committees involved in the development of codes of practice and construction procedure standards. He is also a barrister and has served on various tribunals and appeals boards.

Professor Hongxing Yang (Project 5)

Professor Hongxing Yang
Professor
Department of Building Services Engineering

The team developed a way of coating glass with a durable transparent skin of titanium oxide which is self cleansing and relatively cheap. After TiO2 is illuminated by UV light, organic "grimes" are broken down into water and carbon dioxide. The skin is also hydrophilic, i.e. fully wetting, and dust is readily washed off by rain. The team explored the effects on transparency and the self cleansing properties of three different sizes of titanium oxide particles in the skin. There is a trade off here. More transparency means less self cleansing.

Professor Yang has spent 30 years in renewable energy research in China, the UK and Hong Kong. He leads a Renewable Energy Research Group nested within the University's Research Institute for Sustainable Urban Development. His team is expert in wind, solar and ground heat sources of energy for big building complexes. This includes research into solar panels, vertical axis wind turbines and concrete piles which double up as heat exchangers, when buildings are being heated or cooled.

Dr Daniel C.W. Tsang (Project 6)

Dr Daniel C.W. Tsang
Assistant Professor
Department of Civil & Environmental Engineering

Compared to some other places, Hong Kong is poor at recycling wastes. The research team produced panels of superior sound and heat insulation properties, where the wastes content is as high as 99%. The wastes consist of wood, bamboo and plastics. The other 1% are chemical coupling agents which effectively act to 'fuse' the crushed plastic and timber components into a single strong, dimensionally stable material. The process enables production of a variety of moulded shapes.

Dr Tsang, who joined HKPU in 2012, after research experience at the Universities of Canterbury (NZ), London and Stanford, is a specialist in land remediation, wastes recycling and wastewater treatment. His research emphasizes a strong link to real life practical situations in developing cost effective, minimum impact solutions, based on natural and engineered systems.

Dr Lin Lu (Project 7)

Dr Lin Lu
Associate Professor
Department of Building Services Engineering

This concerns the potential for building foundation bored piles to 'double up' as heat exchanger components of a building a/c and heating system. A long spiral fluid carrying tube is cast within the concrete of the pile so that ground heat can be 'pumped' into the building in winter and waste building heat stored in the ground in summer. The team's analytical model can calculate temperatures anywhere within the pile concrete and anywhere in the surrounding earth. The range of stresses in the concrete due to long term temperature swings, superimposed on the loading stresses, is reassuringly small at 3MPa compressive to 2MPa tensile.

Dr Lu's current research and consultancy interests include renewable energy applications and technology development, green building nanomaterial development, and fluid mechanics and heat/mass transfer related to building studies.

Professor J.H. Yin (Project 8)

Professor J.H. Yin
Chair Professor of Soil Mechanics
Department of Civil & Environmental Engineering

The project was to develop and test two fibre optic strain gauges for use in the long term monitoring of flexible asphaltic road pavements. The FBG gauge (Fibre Bragg Grating) measures strain at a point and the BOTDA gauge (Brillouin Optical Time Domain Analysis) measures the average strain over a user determined distance. The gauges worked well in the sub grade, the sub base and the black top layer of an experimental test rig.

Professor Yin's research interests include many aspects of geotechnical engineering from the fundamental behaviour of soils, to applications of synthetic soils reinforcement materials and to applications and developments of advanced instrumentation the better to study ground movement. He is Vice-President of the International Association for Computer Methods and Advances in Geomechanics.

1. Textile Reinforced Shotcrete for the Repair and Strengthening of Fire-Damaged Reinforced Concrete

Background and Objectives

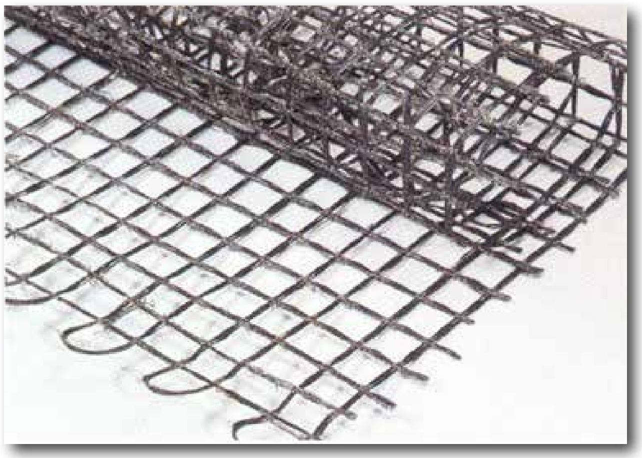
Recent fires in the Lion Rock Tunnel and Mongkok Garden demonstrated that fire can severely damage a reinforced concrete (RC) structure, resulting in extensive cracking and spalling of concrete and a substantial loss of load-carrying capacity. Most fire-damaged structures are repaired or strengthened, as this is usually more cost-effective than demolition and re-construction.

Traditionally, a concrete or mortar overlay system, reinforced with steel bars/mesh, has been used to repair and strengthen damaged RC structures. In recent years, this method has been largely replaced by an externally bonded fibre reinforced polymer overlay (FRP), popular because of its high tensile strength-to-weight ratio, excellent corrosion resistance and ease of implementation on site. However, this FRP strengthening technology is of limited use for indoor applications, because of fire resistance concerns. The FRP polymer matrix and the bonding adhesive perform poorly at elevated temperatures.

The PI, Dr J.G. Dai, therefore, explored an innovative textile reinforced shotcrete system (TRS) for repairing and strengthening fire-damaged RC members. The textile is of 'basalt' ie of rock material and therefore as resistant to fire as the engineered cementitious shotcrete (ECC) matrix in which it is embedded. TRS retains the key advantages of both the traditional overlay system's fire resistance properties and flexibility in construction of the new externally bonded FRP system. The steel reinforcement and mortar of the traditional overlay system, is replaced by a non-corrosive, fire resistant and high strength textile reinforcement enabling the usual cover to be reduced (and, therefore, the self-weight of the structure). The externally bonded FRP overlay strengthening method cannot compete with the TRS/ECC system when fire protection is necessary.

Experimental Program and Findings

The basalt textile is an environmentally friendly non-metallic material, similar in geometry to steel meshes, and easy to handle on site. The ECC matrix is a special high-performance fibre-reinforced cementitious composite of ultra-high ductility. The material's fracture strain is greater than 4%, about 400 times that of conventional mortar.



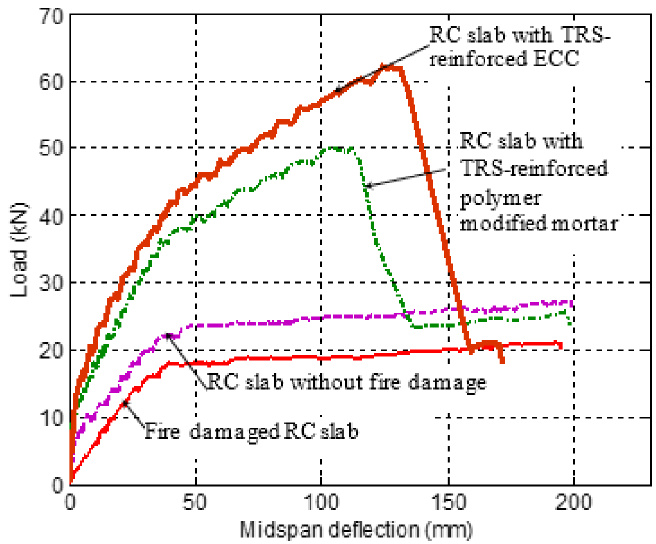
Basalt textiles

Project Outcomes

Eight RC slabs [1000*300*100mm] were exposed to a standard fire in a furnace to induce concrete spalling, simulating the damage encountered in actual fires. After treating the damaged RC slab surfaces, the ECC was mixed and sprayed on the slab soffits. The basalt textiles were then attached with a finishing layer of ECC. The above process was repeated in cases with multiple textile layers.

After sufficient curing the TRS-strengthened RC slabs were subjected to four-point bending tests. The load-deflection responses for some RC slabs are shown alongside. It is clear that the load-carrying capacity of those fire-damaged RC slabs strengthened with the TRS system were significantly greater (by 70%~200%) than their un-strengthened counterparts. The ECC matrix was also found to be more efficient than conventional polymer modified mortar, in that a very useful characteristic of the TRS/ECC is the formation of many small cracks in the layer. This helps prevent interfacial debonding between the TRS layer and the slab substrates, leading to increased member strength and ductility.

Concrete spalling after fire exposure



Load-deflection curves of reference slabs and fire-damaged slabs with textile-reinforced conventional mortar and ECC.

2. Position Tracking on Site

The project concerns the ability to continuously track the positions of moveable items on site at a reasonable cost. The movers might be plant items and major tools, say, and even personnel. GPS systems cannot be guaranteed to achieve accuracies within 5-10m in Hong Kong, which is too imprecise for useful site application. Indoor positioning systems exist, however, with varying degrees of accuracy, motivating **Professor Wu Chen** to develop an inexpensive indoor positioning system, accurate to within 1.5m, in a laboratory at HKPU. This system was then easily transferred to work outside at construction site scale where it achieved worst accuracies of the order of 0.5m, precise enough for site management purposes. The longer 'sight' lines possible out of doors, help to reduce orientation errors.

Background

There are several methods used for the indoor positioning of moving targets, based either on wireless signal propagation or on inertial navigation. The former method can achieve centimetre level accuracy indoors but only at high cost. The inertial approach becomes increasingly inaccurate with time since it sequentially tracks successive distances moved and the orientation of each move with a consequent accumulation of errors. To achieve the 1.5m indoor accuracy above, the wireless signal propagation model was improved by the PI, taking advantage of a new and inexpensive distance measurement device, based on the PAN 5375 chip provided by Nanotron Technologies.

System Overview

The system essentially consists of a number of fixed in position 'routers', strategically located about the site which are able to measure the distance to a 'mover', (any number in principle) and report that distance to a 'coordinator' unit. The latter sends its calculated information to a site office computer(s). The routers and movers each carry a transmitter/sensor with an associated ID and as long as enough routers (at least three) can communicate well with a mover, the location of that mover can be estimated accurately enough even though there is no bearings information. The receiver device is small, and could be made very small, for an individual to wear with negligible inconvenience. The cost of these devices may be as little as around HK$200. For a medium sized compact site (as opposed to a linear site) 6-10 routers would be enough. The overall cost therefore is in the low thousands of dollars, not even the tens of thousands, unless a large number of movers were to be included. The biggest challenge may lie in locating the routers in positions where they can be fixed and left there for longish periods of time without damage. Not stated above, the system works in 'real time' so movers can also be tracked while travelling.

The Work Done and Results

The team developed all the hardware integration of the range measuring chips and the communications system and wrote the software which enables the tracking of movement data in real time and its transmission to the coordinator. New robust positioning algorithms were developed to significantly reduce the effects of large distance errors (or outliers) on final positioning results.

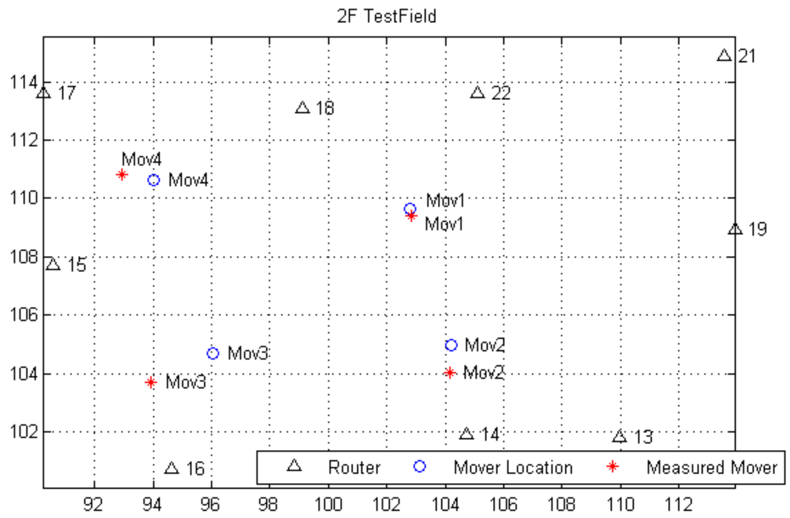
Special 'calibration' software was also written to reduce the inherent instrument error in any ranging measurement. This software was able to reduce indoor ranging errors by the order of 1m, roughly halving the uncalibrated distance errors.

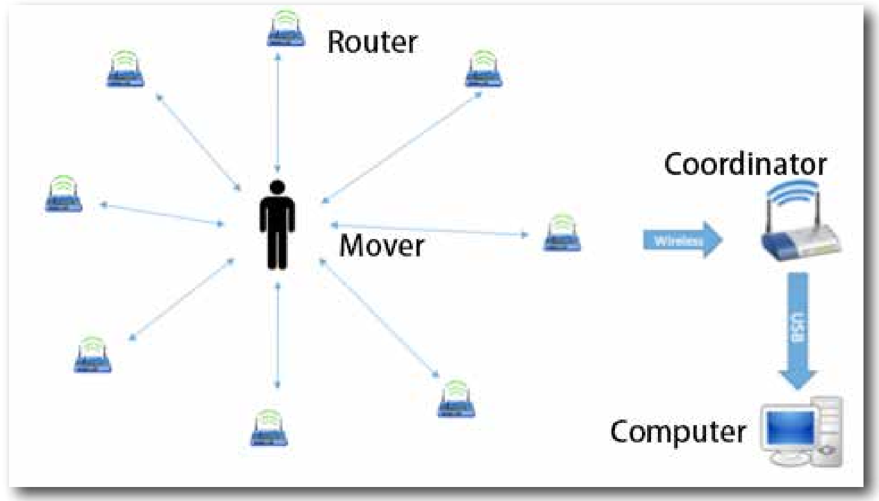
Project Outcomes

An outdoor experiment included four movers. The actual X and Y coordinates are given below (in metres) and the differences between actual locations and those measured by the system are given in the brackets.

X	92.96 (-0.27)	88.75 (-0.29)	104.94 (0.31)	94.97 (0.28)
Y	100.90 (0.35)	100.07 (-0.03)	102.84 (0.26)	97.55 (-0.63)

The worst error is 63cm. The mean of all eight errors is 30cm. Taking the largest diagonal, the new system puts Mover 4 at 69cm distant from its true position.





3. Maximising Indoor Air Quality during Building Maintenance Work

Background

Building maintenance and renovation work considerably raises dust levels during structural, plastering and tiling work and harmful volatile organic compounds (VOCs) when using solvent based paints. Air conditioning systems, too, can cause poor air quality conditions unless regularly maintained and cleaned thoroughly.

The funds for this project were used to measure the indoor pollution levels being reached and relate the values to recognized safety standards. The specific motivation for undertaking this study was (1) to investigate whether air quality problem arise from the execution of certain common types of maintenance works and advise on possible health effects on tenants and maintenance workers with reference to relevant health standards (international and local), (2) to evaluate the removal efficiencies of control devices for airborne pollutant reduction by on-site measurement, and (3) to make recommendations on possible improvements in the maintenance works process so as to lower pollutant concentrations and harmful emissions to acceptable levels.

The team lead by Professor Shun-cheng Lee made measurements on a representative sample of residential and commercial buildings undergoing renovation and hotel rooms in service.

Findings

1. The dust caused by concrete plastering and tiling work is hazardous because of fine particles suspended in the air which can be inhaled. Such 'respirable suspended particulates', or RSP, are graded by size with a PM number, such as PM_{10}, $PM_{2.5}$ etc. The measured quantities at any particular size are expressed in units of 'weight per unit volume'. Particle sizes smaller than PM_{10} arte of concern because those particles can pass through the throat and nose and enter the lungs. Inhaled particles can remain in the lung and cause respiratory diseases.

   Over a period of 8 hours the worst case of particulate pollution measured was 17.62mg/m^3, much more than safety guidelines permit. The US OHSA (occupational safety and health administration) gives a Permissable Exposure Limit - Time Weighted Average (PEL-TWA) of only 5.0mg/m^3.

2. The worst case measurement of VOC due to the use of solvent based paints was 27241ppb (parts per billion). This was very much greater than the US OHSA's Permissable Exposure Limit-Short Term Exposure Limit (PEL-STEL) of only 2000ppb.

3. As for hotel rooms the team found it important to keep the ventilation system well cleaned. The effect of maintaining clean air ducts, in broad terms, is to improve IAQ by 25% for both $PM_{2.5}$ and bacteria.

4. The team took the opportunity to test the effect of its own developed air purifier on the IAQ of hotel rooms. The purifier was equipped with activated carbon, particle filters and an electrostatic precipitator. Tests were performed before and after the installation of the purifier and it was found that the purifier removed $PM_{2.5}$, total VOC and bacteria by 24-28%, 10-16% and 45-51%, respectively.

Project Outcomes

Reccomendations

1. When renovation is taking place, the enclosure should be sealed off as tightly as possible, from the rest of the building, the renovators, of course, wearing protective masks.

2. The frequency of passage through the enclosure exit door should be minimized.

3. The enclosure should be as well ventilated as possible, especially when painting.

4. Dry Spray Ferrocement Jackets for Column Strengthening

Background

Hong Kong is located in a region of moderate seismicity but, unlike the neighbouring province of Guangdong, has no earthquake code for the guidance of structural engineering designers. Before very long, a seismic design code for buildings will be in force in Hong Kong and the strengthening of many existing structures will be necessary. This project was concerned to explore the extent to which in situ columns could be strengthened simply by adding a ferrocement jacket, which would act to confine columns under axial loads.

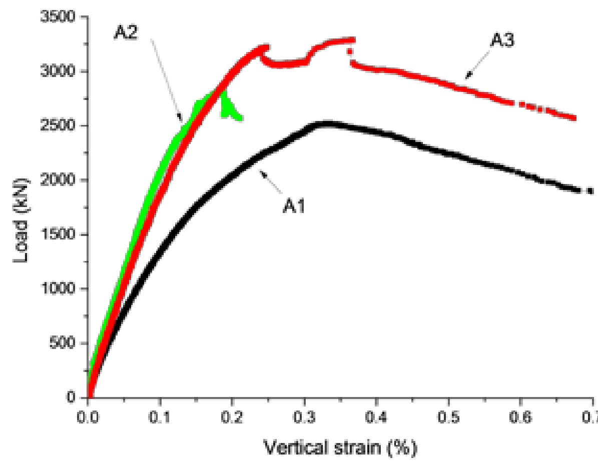
Resistance to fire has always been an important design criterion for structures. A ferrocement jacket provides better fire resistance than other forms of strengthening, being a material fully compatible with the concrete of the column being strengthened. Recent studies led by Dr Eddie S.S. Lam, in conjunction with the company Freyssinet Ltd, have demonstrated the successful application of ferrocement to the strengthening of columns and beam-column joints. The motivation behind the study, inter alia, was the shortage of labour both locally and worldwide. In addition to the effect on column strength, the research also studied the 'conctructability' of dry spray shotcrete to form ferrocement jacketing, as a means of shortening construction time, and reducing the labour required for the coming large programme of column strengthening to take place throughout the Hong Kong territory.

The Findings

To assess both constructability and quality of ferrocement jackets, square columns were given ferrocement strengthening jackets as replacements for the usual concrete cover. A ferrocement jacket is a composite of dry spray shotcrete and steel wire mesh. The technology is not new but the normal guidelines on the proper use of dry-spray shotcrete have been refined as a by-product of this study and new guidance has been added. These relate to wire mesh installation, applying the shotcrete and to surface screeding. Wire mesh, for instance must be fixed at least 5mm clear of the substrate before cement is sprayed, to enable the creation of a sound ferrocement composite jacket. Spraying is to take place from bottom to top, 0.5-1.0 metres distant from the substrate and perpendicular to it, so as to achieve full compaction.

12 no. columns were tested to failure. Test results show a roughly 30% increase in load carrying capacity if the concrete cover is replaced with a ferrocement jacket. The enhancement is particularly noticeable for those columns detailed to comply with the pre-2004 Concrete Code. The 2004 code and its revised 2013 version, require column links (horizontal steel loops encircling the vertical main reinforcing bars) to be much closer together than previously, providing tighter confinement to the column's concrete. Most buildings to be strengthened will pre date 2004.

240 link spacing set	No jacket A1	Two mesh layers A2	Four mesh layers A3
Max Load	2522kN	2842kN (12.7%)	3292kN (30.5%)
Max Stress	37.5MPa	42.6MPa (13.7%)	49.8MPa (32.9%)



Load-Strain plots of columns with link spacing 240mm

Project Outcomes

4 sets of three columns were tested. All 12 columns were reinforced with 20mm deformed bars, representing 1.4% of the column cross section. For each set of 3, column links were spaced at 240,185,130 and 75mm respectively.

There was no sprayed on jacket for the first set of columns. The second set was strengthened with a ferrocement jacket containing two layers of 25mm mesh squares and the third set with four layers of 50mm mesh squares. The wire of the meshes was of diameter 2.04mm and strength 528MPa. The 4 mesh jacket increased load capacity by 30.5% and the 2 mesh by 12.7% for the 240mm link spacing cases. The comparable figures for the 185mm link spacings were 23.8% and 12.1%.

These results provide new information for those deciding on the strengthening method to be employed on the upcoming programme of retrofitting.

Project Outcome

Columns are structural elements which transfer a building's weight to the foundations. To prevent a building collapse due to deterioration or an earthquake, strengthening of its columns may be judged necessary. This study demonstrated that ferrocement jacketing is a viable option for a big programme of columns strengthening. This is mainly because it is easy for unskilled workers to adapt to, and column jacketing needs only two men.

Testing of a strengthened column in Structural Engineering Laboratory

Application of dry spray shotcrete (jointly with Freyssinet)

5. A Cost Effective Self Cleansing Glass Coating

Introduction

A self cleaning glass curtain wall can cost US$10 to US$20 per sq. metre, as opposed to only US$1 for glass which is non-coated.The usual coating processes (chemical vapour deposition, 'sputtering' technique and others) are very expensive requiring intense heat and high vacuums. Professor Hongxing Yang's team have developed a process which brings coating costs down to about US$1.5 per sq. metre.

The Coating

The coating consists of a TiO_2 (titanium oxide) paste which is very uniform and can be cheaply silk-screened on to glass at normal temperatures in much the same way that designs are silk screened on to clothing. The paste is hydrophilic, i.e. fully wetting. Rain water spreads over the surface freely and washes away any dust which may also have settled on the glass surface. When sunlight's UV (ultra violet) impinges on TiO_2, organic 'grimes' are broken down into water and carbon dioxide, the coating performing a photocatalysis function.

Three pastes were trialled, which included TiO_2 particles of about 3000nm, 250nm and 50nm respectively (coatings A,B and C on the graphs alongside). The larger size corresponds roughly to the wavelength of light and much scattering of the light occurs when it hits the paste coating with particles of that size. The effect is that the glass is not sufficiently transparent to be useful as a window, but the self cleansing is particularly good since most of the light interacts with the titanium. The glass appears to be translucent and white.

The 250nm sized particles are suitable for windows but there is a 30% loss of transmission and the window has a bluish tinge. The 50nm size appears to be fully transparent with about 80% to 95% of the light getting through compared with plain glass depending on the different wavelengths. The price to pay for this transparency is a weaker photo-catalytic effect and after one hour of exposure to sunlight the 50nm size paste is only about 60% as effective at self cleansing as the 3000nm paste.

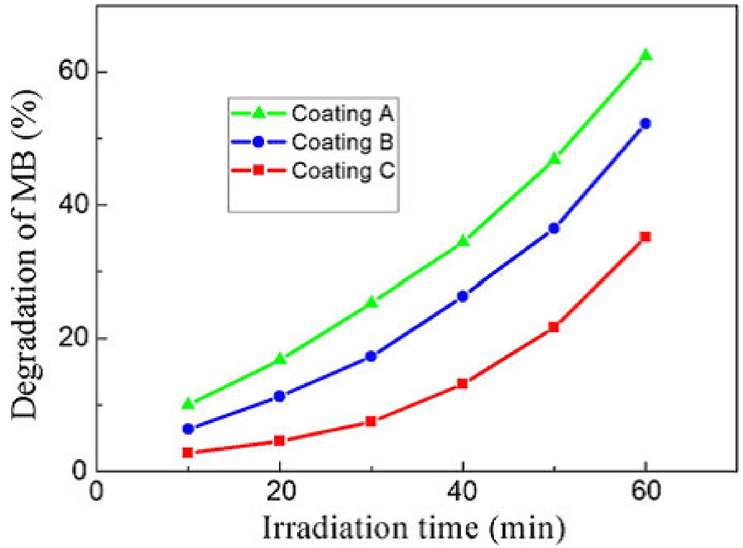
Developing the Coating

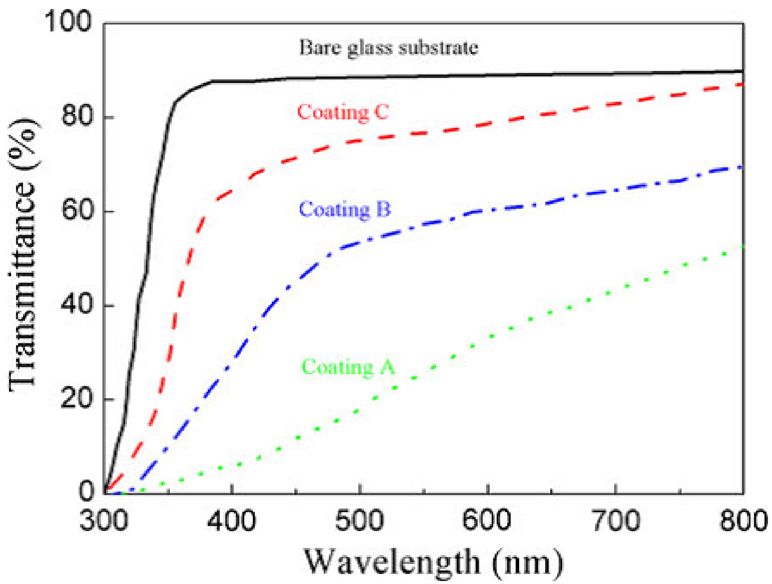
Tiny TiO_2 particles 'aggregate' together with strong bonds and the challenge for the research team lay in breaking down such aggregates as far as possible and dispersing only fine particles throughout the paste. The fundamental particle size is less than 25nm. For the coarsest mix above, particle aggregates varied between 200nm and 5000nm, and averaged 180nm in the next mix. In the final mix, the maximum aggregate size was 80nm and the paste looked smooth even at a magnification of 10,000. The inset picture represents a magnification of 50,000.

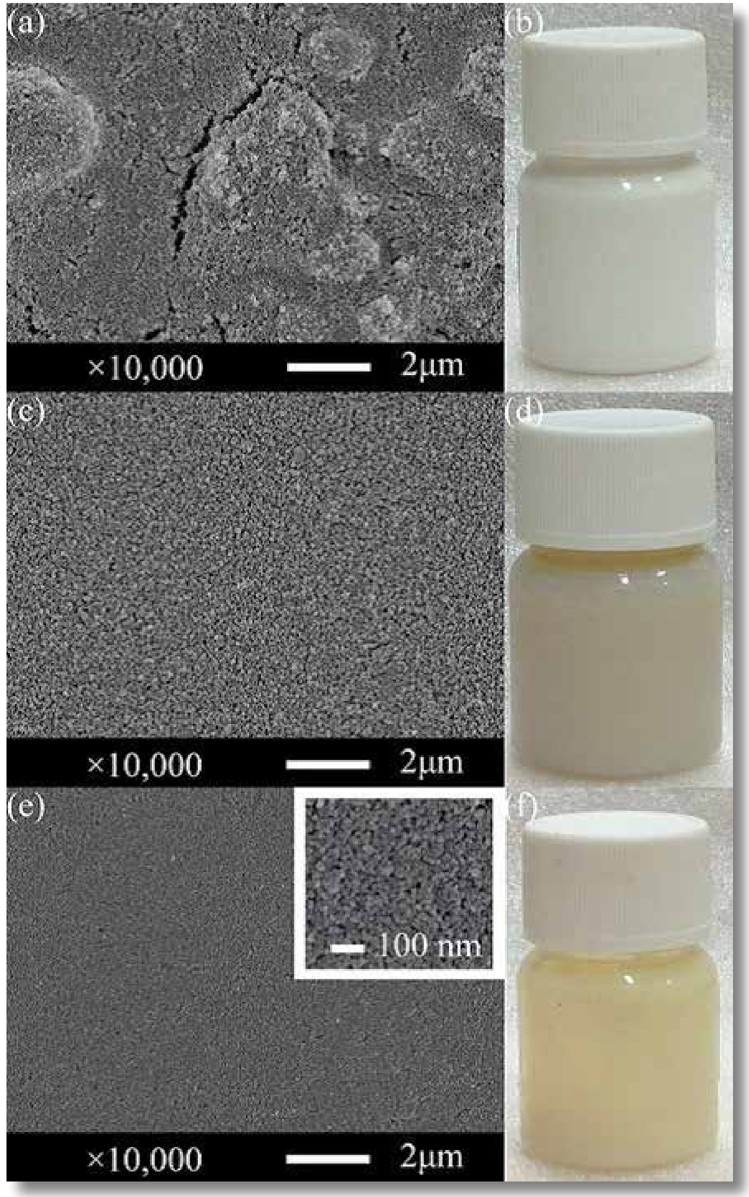
The aggregates were broken down by a ball mill grinding process. The balls were made of ZrO_2 (zirconium oxide) of average diameters 2.0, 1.0 and 0.15mm respectively for the three mixes above. The mix of TiO_2 powder and grinding balls was rotated for 12 hours of grinding at 700rpm followed by a complex process to separate the TiO_2 paste from the grinding balls. The 0.15mm balls were the ones found to disperse the aggregates the most effectively.

A very fine screen, 0.04mm thick, placed on the glass surface is then smeared over with the paste using a rubber blade. The screen 'printed' glass was then sintered at 450 degrees celsius to form a hard and durable surface finish.

Project Outcomes







6. Wood Plastic Composites from Timber, Bamboo and Plastic Wastes

The Achievement

The research team led by Dr Daniel C.W. Tsang developed a new 'wood-plastic composite' (WPC) material made almost entirely from waste timber, including bamboo, and waste plastic, with less than 1% of added chemicals. Timber content can be between 30% and 70% and plastic between 70% and 30%. The coupling agents and added chemicals are crucially important in forging compatibility between wood and plastic and hence a good mechanical strength. Because they might be the subject of a patent, details are not included here.

Apart from the mix, the team also developed a serial manufacturing process at pilot scale.

Panels were made from the material and tested. The products are anti bacterial, anti fungal, waterproof, fire resistant, low in heat conductivity and sound transmission, as well as being structurally tough. The added chemicals helped with some of those properties. The material can be moulded to virtually any shape.

The Technology

Materials

Packaging waste timber and most commonly recycled plastics can be used. The team mostly used masson pine and waste plastics obtained from the Eco-Park in Hong Kong. The latter included poly-propylene, high density poly-ethylene and low density poly-ethylene. The added chemicals, as above, improved the compatibility of the timber and plastic and the functional properties of heat and noise transfer, fire resistance and waterproofing. A major challenge was the successful selection of the chemical additives. The wood and plastic compatibility, for example is achieved chemically by coupling agents. Our products present excellent waterproofing without addition of repellent agents.

Main Machine

A co-rotating twin-screw extruder (SHJ-20B, Giant) was used for all compounding. The standard compounding screw included conveying elements and kneading discs. Screw speeds were in the range 100-500rpm. Throughput, Q, ranged between 2 and 10kg per hour. The process temperature was at 180-220 degrees celsius en route between the initial hopper and the die at the end of the process.

The Process

Firstly, wood waste and plastic are crushed by machine and sieved into standard sizes. Secondly, the crushed wood and crushed plastic are dried in an oven at 80°C for 24h. Plastic and wood, coupling agent and additives are then dry mixed thoroughly before feeding into the twin-screw extruder and compounded as above. The melted mixture, at 220 degrees celsius is then injected into a mould(s) and compressed by a pressure machine. After about 20 mins of air cooling, the final products are demoulded.

This process represents an important contribution to the local recycling industry and creates a new market outlet for waste timber and waste plastics.

Project Outcomes

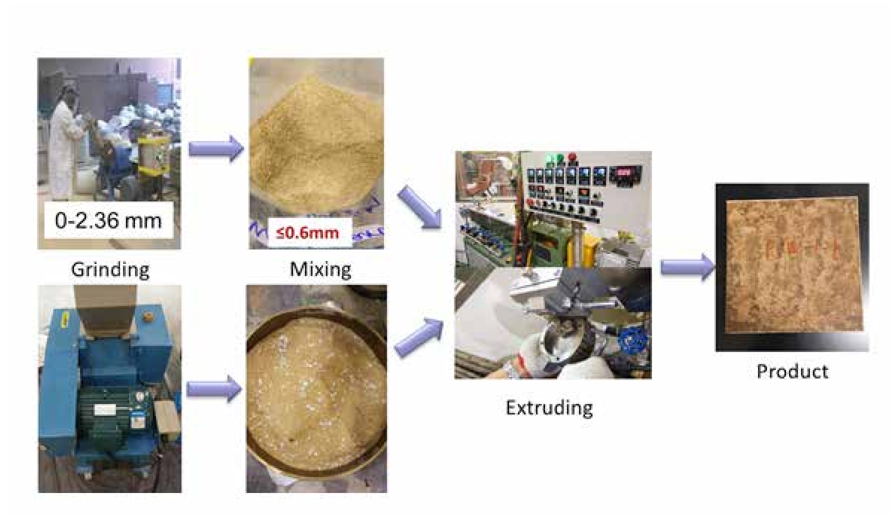
The Test Performances

Panel products achieved excellent impact noise reduction results. The reduction rate for structure-borne noise frequencies (20-100Hz) was 5 times that of normal concrete panels. The reduction achieved was as much as 30dB(A).

Other performance results include:

- Water absorption: <0.5% (24h water immersion). Standard: 2% (GB/T 24137-2009)
- Thickness swelling: <0.1% (24h water immersion). Standard: 0.5% (GBT 24508-2009)
- Thermal insulation: thermal conductivity was below 0.21$Wm^{-1}K^{-1}$. Standard: 0.3$Wm^{-1}K^{-1}$ (BS EN 13986)
- Anti-bacteria: 100% disinfection rate (Escherichia coli)
- Anti-fungus: 100% disinfection rate (Coriolus versicolor)
- Anti-algae: 100% disinfection rate (Chlorella vulgaris)

Outdoor Applications



Process of WPC Manufacture

7. Temperature Induced Stresses in Heat Exchanger Foundation Piles

Background

The earth beneath a building can be used as a source of heat to warm the building in winter and as a sink for the extracted heat when cooling the building in summer. The heat exchanger foundation pile of this project consists of a long spiral coil of HDPE (high density polyethylene) tube, cast integrally with the concrete of the pile just within its circumference. The heat exchange fluid which circulates through this tube is hot in summer and cold in winter. The concrete of the pile, therefore, warms up in summer and passes on that heat to the cooler surrounding earth. The reverse process occurs in winter when heat is withdrawn from the earth to warm the building. Such piles are known as Energy Piles. The pile performs its normal building support function but doubles up as the heat exchanger in a 'ground coupled heat pump' system, at minimal additional cost and no requirement for additional land. This 'piggy backing' on the support piles almost eliminates the initial costs and space needs of a stand-alone heat pump system.

In addition, such energy piles provide good tight contact between the cast in HDPE coil and the concrete encasing it, as well as between the perimeter of the pile and the surrounding earth. This results in a considerable reduction in thermal contact resistance, significantly improving the heat transfer efficiency between earth and coil.

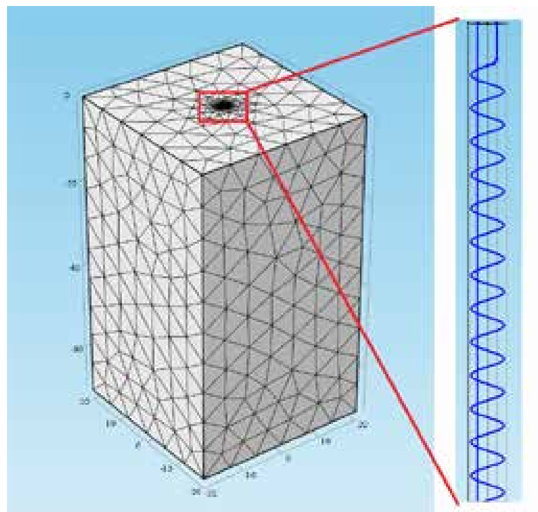
In service, the temperature variations in the concrete of the energy piles can be up to 20 degrees celsius. The swings in temperature in the surrounding earth are much less than that and temperature induced stresses, therefore, are set up in the pile, because the pile is not able to freely expand and contract, due to end fixity conditions and the frictional forces between the pile and the surrounding earth. These stresses are superimposed on the compressive stress already existing in the pile caused by the weight of the building.

The aim of this project, therefore, was to model and study the heat transfer performance of the spiral coil energy pile and to assess the size of the temperature induced stresses in the pile and whether they might prove detrimental to the structural integrity of the pile.

Findings

Based on Green's function theory and Jaeger's instantaneous line-source heat transfer model, a new composite analytical model, was established which successfully takes proper account of the thermal properties of the pile and soil. The spiral coil carrying the fluid was modelled as a series of equivalent rings. The model represents the heat transfer processes and output temperatures both in the concrete of the pile and in the surrounding earth. These temperatures can be calculated for locations at any specified radial distance from the centre of the pile and for any period of time after the start up of the heat pump system.

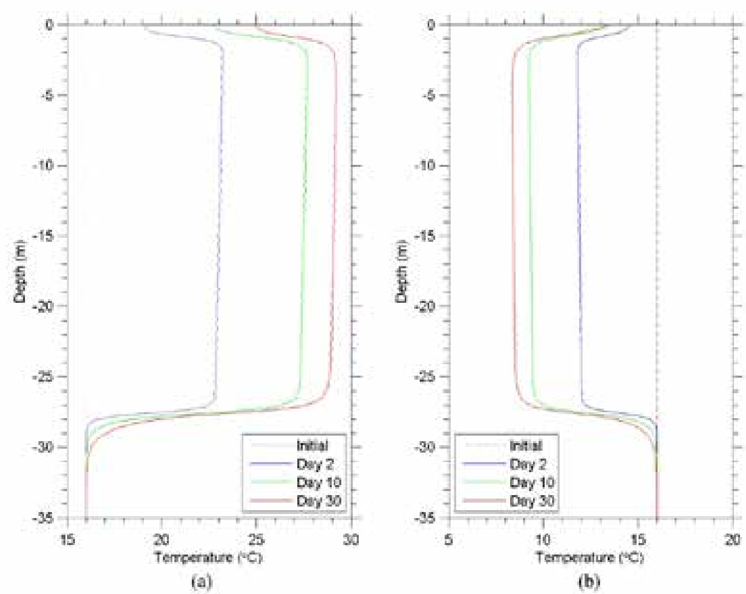
The thermo-mechanical behaviour (i.e. the induced thermal stresses) within the concrete of the pile was also investigated using a 3-D simulation model. The numerical results show that the maximum thermal stress exists in the middle of the pile. The maximum temperature rise in the pile, as the building is being cooled, was 11°C, and the consequent axial thermal compressive stress was 2.262MPa. A tensile stress of 1.316MPa due to temperature occurs when the building is being heated, as the pile temperature drops from 16°C to 8.3°C. The stress change induced by a unit temperature increase in the pile is 0.205MPa in compression per degree celsius.



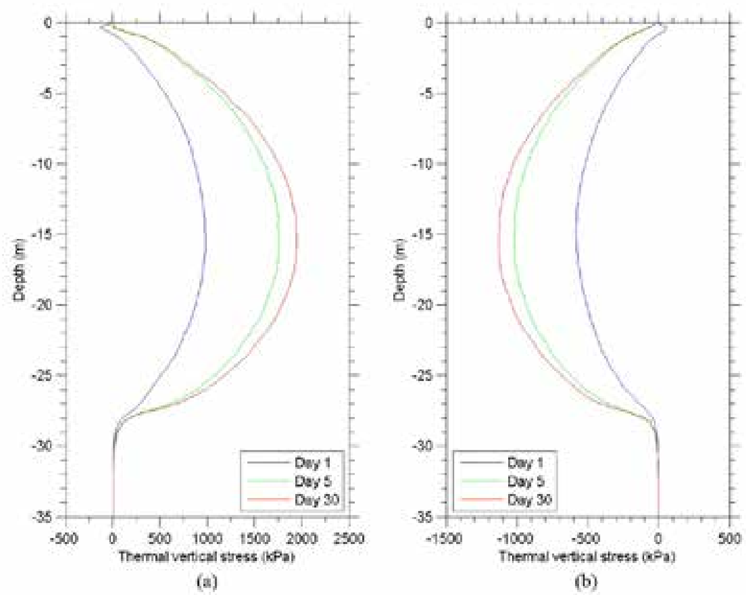
Finite element mesh used in the simulations

The maximum compressive stress is very small in relation to the likely compressive strength of the concrete. The tensile stress is about 25% of the likely tensile strength of the concrete (always much less than compressive strength) but is of the same order of magnitude. These small tensile and compressive stresses would usually be superimposed on the much larger compressive stress already present in the pile due to the weight of the building.

Because of the continual fluctuations in axial stress over time due to temperature swings in the pile during the operational life of an energy pile the long-term thermo-mechanical behaviour of the spiral coil energy pile ought to be thoroughly investigated if only for purposes of reassurance. Cracks could possibly occur during long-term operation, if the building load in the pile does not remain compressive at all times for some reason. Experiments are needed to explore the pile's long term behaviour in this respect.



Axial temperature distributions in the pile (a) cooling and (b) heating operation.



Axial distributions of the thermal vertical stresses in (a) cooling and (b) heating operation.

8. Fibre Optic Strain Gauge Development for Flexible Asphaltic Road Pavements

Background

Part I of this report gave the results of a project designed to study the application of two advanced optical strain gauges attached to soil nails for slope stability long term monitoring purposes. These gauges cannot be bought 'off the shelf' but rather have been designed, made and tested by the HKPU team. Whether gauges could also be designed which would prove suitable for flexible pavements was the key question motivating the PI, Professor J.H. Yin. The aim was to develop gauges suitable for monitoring strains in the different sub-grade, sub-base and asphalt layers of the typical black top flexible pavement. The maintenance of roads is a costly business and often there is little or no warning of quite substantial pavement collapses. Long term monitoring can give early warning if a crack or void occurs, otherwise unseen, in a road sub-base. This gives the opportunity to take cheaper preventive action while the damage is still localized.

The Two Gauges

There are two types.

One, is based on the well known scattering of light phenomenon by a Bragg Grating. A grating situated across an optical fibre exhibits different light scattering characteristics depending on the temperature and strain at that point along the fibre. Such FBG (Fibre Bragg Grating) gauges, once calibrated, can measure strains in the road at those points where a fibre (with its grating) stretches or contracts in line with the material of the road layer concerned.

The Second, known as a BOTDA (Brillouin Optical Time Domain Analysis) gauge, measures an average strain over a distance between two anchor points set securely in the road layer material. Unlike the FBG gauge, the BOTDA gauge is particularly suitable for locating those sections of road where a crack or void appears, since the section of optical fibre within which the crack somewhere occurs, will exhibit a sudden large increase in strain.

The FBG gauge has a resolution of 1 microstrain and the BOTDA of 2 microstrain. Both gauges have a strain range of 30000 microstrain (i.e. 3% strain).

Robustness

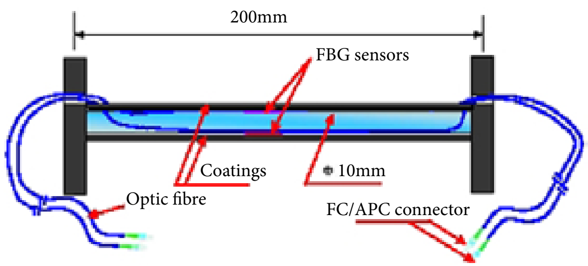
The team has developed ways of protecting these gauges and sheathing the runs of optical cable against the rigours of site construction operations. An FBG sensor plate gauge has up to 4 gratings glued to both sides of a 3mm thick steel plate, 480mm long and 20mm wide with several coats of resin protecting both gratings. The outer coat can resist high temperatures, to cope with hot asphalt. The plate is flexible enough to bend in full compliance with the vertical movements of the road pavement, in response to wheel loads. FBG gauges can also be used singly. The design is such that each end of the gauge is securely fixed to the adjacent road material.

The BOTDA gauges are similarly robust at the cable anchor points.

For both gauge types, the optical cable installed is left in a state of pretension so that both shortening strains and lengthening strains can be measured.

Calibration Tests

The gauges were tested in the laboratory under semi-realistic conditions. A section of road was made 1200mm long and 600mm wide in 4 layers to a total of 650mm thick. The normal sub base materials were compacted to real road building specifications. Hot asphalt was brought to the lab for the top layer by 'raiding' a road maintenance site where asphalting was ongoing. A finite element model was also created which was used to show that the buried strain gauge measurements and vertical deflection measurements under a simulated wheel load agreed 'reasonably well' with the calculated FE strains and vertical deflections. Exact agreement would be impossible because of the idealized assumptions made with respect to the behaviour of the FE model materials. That the measurements agreed approximately with theory, including the trends in strain as load was steadily increased, shows that the gauges worked as they were meant to, and are ready to be trialled on a real road.



FBG based asphalt strain sensor

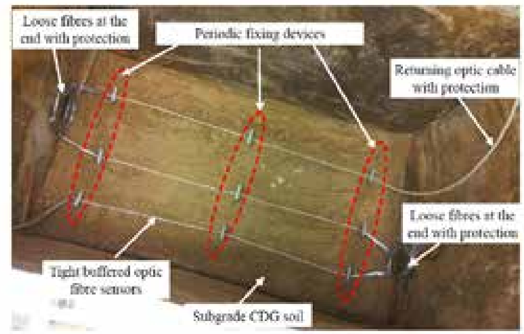


Photo of installation of BOTDA sensing fibre in the subgrade layer

Installation method of distributed strain sensing fibre in the subgrade layer

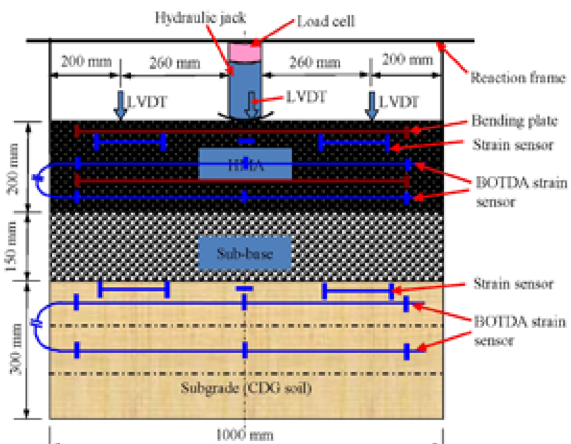
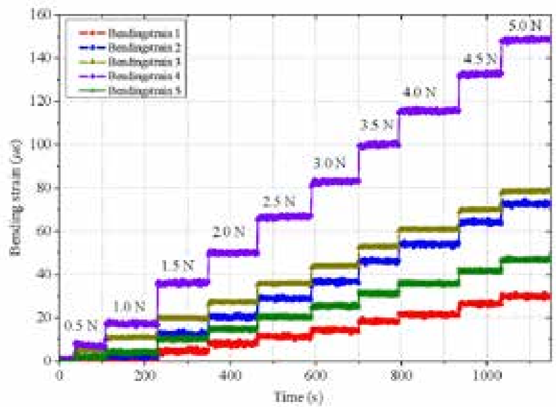


Diagram of various sensors installed in the model test



Calibration results of the sensing beam II

Appendix 1 - The Project Team Members

Project 1 - Textile Reinforced Shotcrete for the Repair and Strengthening of Fire-Damaged Reinforced Concrete

Dr J.G. Dai	Principal Investigator
Dr Wang Yang Gao	Research Fellow
Mr Ke Quan Yu	PhD Student

Project 2 - Position Tracking on Site

Professor Wu Chen	Principal Investigator
Dr Ye Lei	Research Fellow
Mr Wenbin Li	Research Assistant
Mr Duojie Weng	Research Assistant

Project 3 - Maximising Indoor Air Quality during Building Maintenance Work

Professor Shun-cheng Lee	Principal Investigator
Dr Wilco Chan	Co-Investigator
Dr Yu Huang	Research Fellow
Ms Sarah Yau	Senior Research Assistant
Mr Long Cui	PhD Student
Mr Yuan Gao	PhD Student
Mr Zhou Zhang	Research Assistant
Mr Jiaping Wang	Research Assistant
Mr Yeeling Cheung	Research Assistant

Project 4 - Dry Spray Ferrocement Jackets for Column Strengthening

Dr Eddie S.S. Lam	Principal Investigator
Mr Yang Shi Dong	Research Assistant

Project 5 - A Cost Effective Self Cleansing Glass Coating

Professor Hongxing Yang	Principal Investigator
Dr Yuan Hao Wong	Research Felllow
Mr Yan Hu	PhD Student

Project 6 - Wood Plastic Composites from Timber, Bamboo and Plastic Wastes

Dr Daniel C.W. Tsang	Principal Investigator
Professor CS Poon	Co-Investigator
Mr Wang Lei	PhD Student
Ms Chen Si	PhD Student
Ms Zhang Qiqi	Research Assistant
Ms Beiyuan Jingzi	PhD Student
Ms Yu Ka Ming	PhD Student

Project 7 - Temperature Induced Stresses in Heat Exchanger Foundation Piles

Dr Lin Lu	Principal Investigator
Dr Yong Xia	Co-investigator
Dr Yue Zheng	Research Assistant
Mr Deqi Wang	PhD Student

Project 8 - Fibre Optic Strain Gauge Development for Flexible Asphaltic Road Pavements

Professor J.H. Yin	Principal Investigator
Dr Dong Sheng Xu	PhD Student
Dr Lalit Borana	Research Associate
Dr Tony Tong	Research Associate

Appendix 2 - Publications Arising from the Projects to Date

The references below enable interested readers to follow up on any project in more detail.

At this stage, the list is in embryo form only, as most projects were finished relatively recently. Several papers are still undergoing review by journals so cannot yet be referenced.

Project 1 - Textile Reinforced Shotcrete for the Repair and Strengthening of Fire-Damaged Reinforced Concrete

1) Yu, K.Q., Dai, J.G, Lu, Z.D. and Leung, Christopher, K.Y. (2015), Mechanical Properties of Engineered Cementitious Composites Subjected to Elevated Temperature, ASCE, Journal of Materials in Civil Engineering, 27(10), 04014268.
2) Hu, K.X., Gao, W.Y., Dai, J.G., Yu, K.Q., Dong, K. and Fang, L.J. (2015), Experimental Study on the Flexural Performance of Fire-damaged RC Slabs Strengthened with Basalt Textile-Reinforced Cementitious Composites, Industrial Construction, 2015(s), 51-56. (in Chinese)

Project 3 - Maximising Indoor Air Quality during Building Maintenance Work

1) W. Chan, S.-C. Lee, A. Hon, L. Liu, D. Li, N. Zhu, Management learning from air purifier tests in hotels: Experiment and action research, **International Journal of Hospitality Management**, 44 (2015) 70-76.

Project 5 - A Cost Effective Self Cleansing Glass Coating

1) Yuanhao Wang, Lin Lu, Hongxing Yang and Quande Che. Development of high dispersed TiO2 paste for transparent screen-printable self-cleaning coatings on glass, **Journal of Nanoparticle Research**, Vol. 15, No.1384, Jan 2013.
2) Hu Yan, Wang Yuanhao and Yang Hongxing. TEOS/silane coupling agent composed double layers structure: A novel super-hydrophilic coating with controllable water contact angle value, **Applied Energy**, In Press, November 2015.

Project 7 - Temperature Induced Stresses in Heat Exchanger Foundation Piles

1) Wang DQ, L. Lu, P Cui, A novel composite-medium solution for pile geothermal heat exchangers with spiral coils. International Journal of Heat and Mass Transfer 93(2016): 760-769.

Project 8 - Fibre Optic Strain Gauge Development for Flexible Asphaltic Road Pavements

1) Xu Dong Sheng, Development of Two Optical Fibre Sensing Technologies and Applications in Monitoring Geotechnical Structures., Ph.D Thesis , (2014) The Hong Kong Polytechnic University