# SCI CONCRETUS

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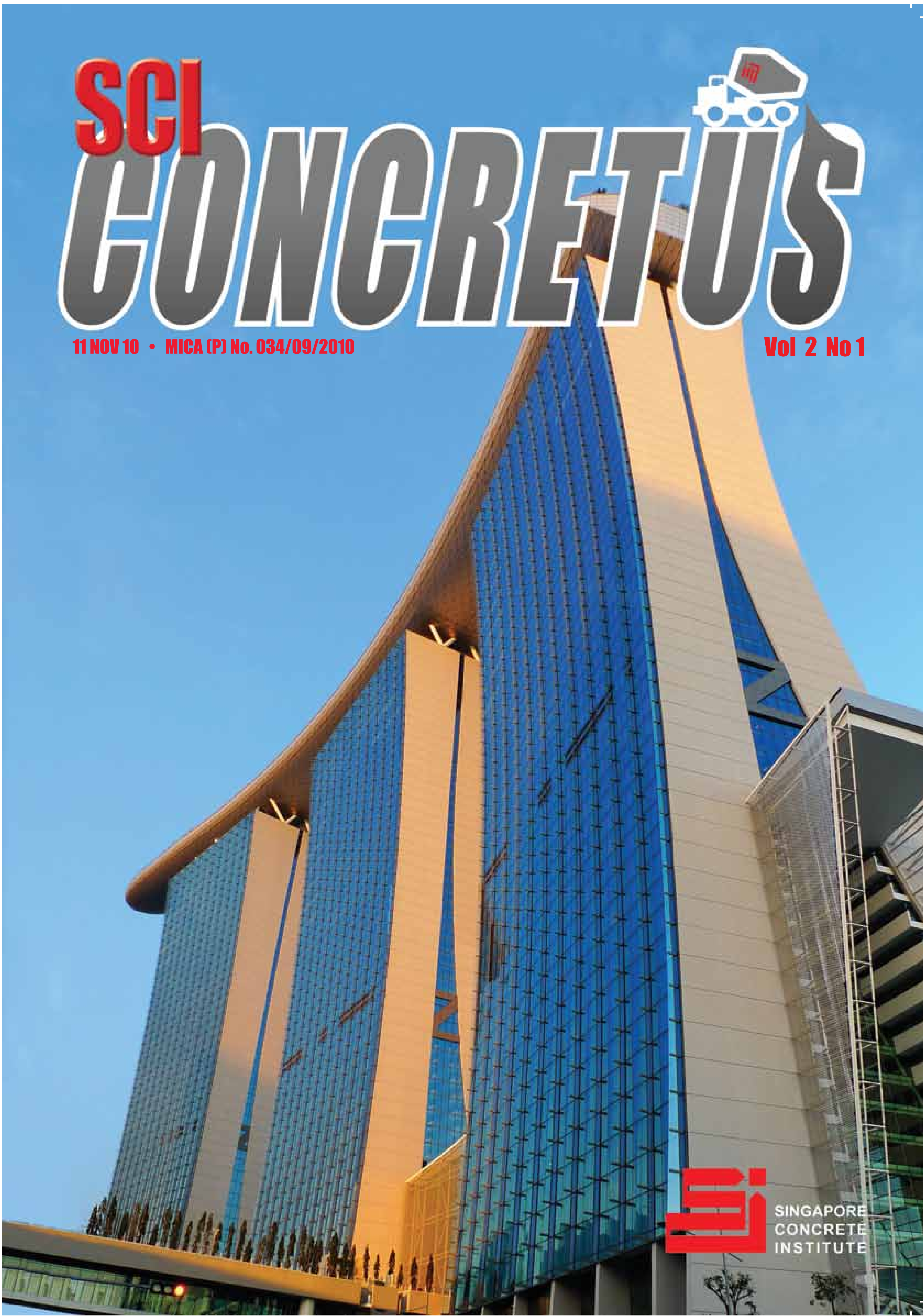

SINGAPORE CONCRETE INSTITUTE

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SCI CONCRETUS • Vol 2 No 1
11 NOV 10 • MICA (P) No. 034/09/2010


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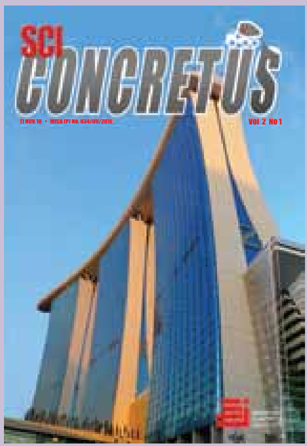


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# President's Message

On this 32nd Anniversary of the Singapore Concrete Institute, our technical magazine-cum-directory, the SCI Concretus, has reached a significant milestone on its first Anniversary with the release of this third issue.

Since its inaugural launch on 17 November 2009, SCI Concretus, the voice of SCI, has garnered a lot of supports from our members, fellow professionals, academics, researchers, concrete technologists and business partners.

The bi-annual magazines, distributed widely amongst institutions, professional bodies, government agencies etc have gained wide readership in its first year of publication. I am encouraged by the warm response judging from the number of interesting technical reports and articles received so far for every issue.

The SCI Concretus has indeed served our members and friends well with its wide ranging coverage of issues and state-of-the-art technology in various fields related to concrete and all its constituents. In today's built environment surrounded by issues of global warming, ever-increasing carbon emission, SCI wish to do our part in promoting knowledge and practices in green and sustainable technologies by focusing more in these areas for our readers.

On behalf of the SCI Board of Directors, I would like to thank all our sponsors, friends and supporters of SCI for their continuing support of this publication. We look forward to your future contribution in making the SCI Concretus a must have publication on every desktop shelf and on-line in every laptop computer.

May I wish all our readers a Season's Greeting!

Oh Lock Soon
President
Singapore Concrete Institute
11 November 2010

**Post Editor's Note**
At press time, SCI learnt of the passing of our past President, Dr Y S Lau on 3rd November 2010. It is of great loss to the professional community and the SCI Board of Directors extends their deepest condolences to the bereaved family of the late Dr Y S Lau.

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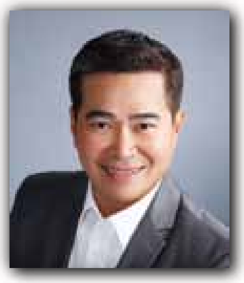

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# Singapore Polytechnic clinches President's Award for the Environment

SINGAPORE POLYTECHNIC SP

Singapore Polytechnic (SP) was awarded this year's President's Award for the Environment (PAE) for its contributions that include staff and students mobilising to protect the environment on campus and also conducting outreach programmes targeting the industry and community.

The PAE is the highest accolade in Singapore for achievements in the field of environmental sustainability. It aims to recognise significant achievements and contributions of individuals, organisations and companies who have had a positive impact and made significant contributions to the local community in helping to sustain the environment.

SP is the first polytechnic to receive the award since its inception in 2006.

An innovation hub made out of 80 percent recycled materials called InnoVillage was also developed. This, together with the development of the Heritage Tree Trail, an innovative learning journey for secondary school students, played a big part in helping SP land the top award.

This article highlights some details of SP's InnoVillage which brings together an eco system of students, academia and industry to exploit the latest technologies in the incubation of products and services. It leverages on this eco system to incubate business, test prototypes and transform them into real products.

InnoVillage showcases SP's commitment to sustainable development and energy efficiency. The site makes use of environment-friendly features that help reduce energy consumption. These include solar-tubes, an emergent and innovative reflective device that brings in natural sunlight into rooms, and the proprietary energy saving dimmers along the common corridors invented by SP staff. A green wall at the entrance also helps reduce temperatures in the adjacent rooms by up to four degrees.

Clean energy solutions such as the solar panel, wind turbine, and prototypes of sustainable living products like the solar kiosk and Southeast Asia's first solar-powered charging station are on display in InnoVillage to let visitors see and experience green technologies.In recognition of its extensive use of green and sustainable solutions in its construction, InnoVillage was awarded the Platinum Green Mark Award in 2010. Eighty per cent of InnoVillage was built using recycled materials which helped to achieve a sizeable cost savings of $4 million. At the heart of Innovillage are various living labs that contribute to the heartbeat of this innovation hub. The 3D Stereoscopic Theatre, DesignWorks, Live Well Collaborative – Singapore, StartUp@SP and The Student Agency are examples of these living labs where creative ideas are gradually morphed into realities.

# A Sustainable and Environmental Friendly Material (Recycled Concrete Aggregate) for Building Construction

*By Tan Poh Seng, Senior Lecturer, Singapore Polytechnic*


## When was it conceived?

This is a joint project between Singapore Polytechnic and Samwoh Corporation Pte Ltd. Final year students from Singapore Polytechnic beginning in 2006/07 participated in the studies over the last several years.

## What does it aim to achieve?

Recycled Concrete Aggregate (RCA) is derived from the processing of construction and demolition waste. So far it has been mainly used for road construction works and non-structural concrete especially in the precast concrete industry. From our preliminary study, it is shown that RCA has a good potential to be used in structural concrete.

This project is a continuation of a study that was conducted using RCA as a replacement for granite in structural concrete.

Structural concrete containing up to 60% of RCA was studied. From the no. of tests carried out, it was found that the strength properties of concrete with RCA were not adversely affected for up to 60% of RCA replacement of granite. In this second part of the study, other engineering properties of concrete with RCA were determined.

The study involved laboratory tests such as compressive strength, flexural strength, tensile splitting strength, permeability, elastic modulus, drying shrinkage and other durability tests. The evaluation was carried out with respect to various grades of concrete containing different proportions of RCA.

## What are the findings in summary?

The study showed that RCA is generally lower in density and has higher absorption as compared to natural aggregates. This resulted in a reduction in the workability of the concrete with increasing RCA content. In view of this, a rational mix design method proposed by the Samwoh Corporation Pte Ltd was used as it can account for the effects of RCA.

The results showed that compressive strength of concrete using RCA is marginally lower than concrete using natural aggregates when more than 50% RCA is used. Other engineering properties such as the splitting tensile strength, flexural strength, elastic modulus and creep of concrete with RCA also showed slightly lower performance as compared to concrete with natural aggregate as RCA content increases. It is envisaged that the slight reduction properties can be enhanced by fine adjustment of the mix design.

## Who is/are the industry/commercial partner?

The Industry Partner in this study was Samwoh Corporation Pte Ltd, a leading integrated construction company and building materials supplier. Samwoh Corporation has an R&D Centre which is equipped with state-of-the-art testing facilities to support our final year students' project. Our students are indeed privileged and honored to be involved in undertaking testing and evaluating some identified physical and mechanical properties of RCA. Students' learning outside the classrooms is enhanced through involvement in this given opportunity by Samwoh Corporation and we will continue to work with the researchers from the company in future.


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# Enduring Concrete: Reducing Carbon Footprints to pave way for Concrete Sustainability

*Nilotpol Kar BASF Construction Chemicals Division Asia Pacific, Singapore*
*KiatHuat Seow, BASF Construction Chemicals Division Asia Pacific, Singapore*

In spite of the dark clouds of the financial crisis that loomed over the construction sector after the boom time a few years back, issues like "green building", "sustainable construction", "reduction of carbon footprints" have been a "top the mind" issue on stake holders of the construction industry value chain.

As various agencies and countries endeavour to come up with a unified approach towards sustainable construction, a simplified approach is to start off with reduction of carbon dioxide emissions to sustain the environment which can be accomplished by calculating the 'carbon footprint' and identifying those aspects of routine construction that consume the most carbon. It is possible to minimise those activities and, where possible, seek sustainable alternatives. For example, one can use a higher quantity of supplementary cementitious materials (SCMs) in concrete rather than pure Ordinary Portland Cement. Apart from the energy savings accrued out of this, other issues like water savings, longevity, safety, productivity (speed of construction) and a resultant lower maintenance costs can be positive attributes in working towards sustainable construction.

Sustainable construction should not be seen as something that is exclusive to expensive projects, as it has the potential to be applied to any development. If even small aspects of a development are switched to more sustainable materials or design this should be seen as a step forward.

## Concrete Sustainability

Concrete sustainability means meeting the needs of concrete today without compromising the ability of future generations to meet their needs. This can aim to be applicable to the construction industry by providing ways of buildings that use less virgin material and less energy, cause less pollution and less waste but still provide the benefits of endurance – longevity – durability that construction projects have brought us throughout history. Apart from aiming at reducing the environmental impact of a building over its entire lifetime, it strives to optimize its economic viability and the comfort and safety of its occupants. Hence we have to mindful of the interdependence between economical, sociological, geographical, geological and biological factors.

Concrete is the second most widely used material in the world after water and the number one man made material consumed. Being the very core of our homes, towns and cities it has a crucial role to play in the future success of sustainable construction. Because of the high volume used however it is still a major contributor to global greenhouse gases. Total anthropogenic emissions are in the order of 20 billion tones and the CO2 that is produced during cement production accounts for around 10% of this. Concrete, it is said, accounts for 7% of the global CO2 emissions.

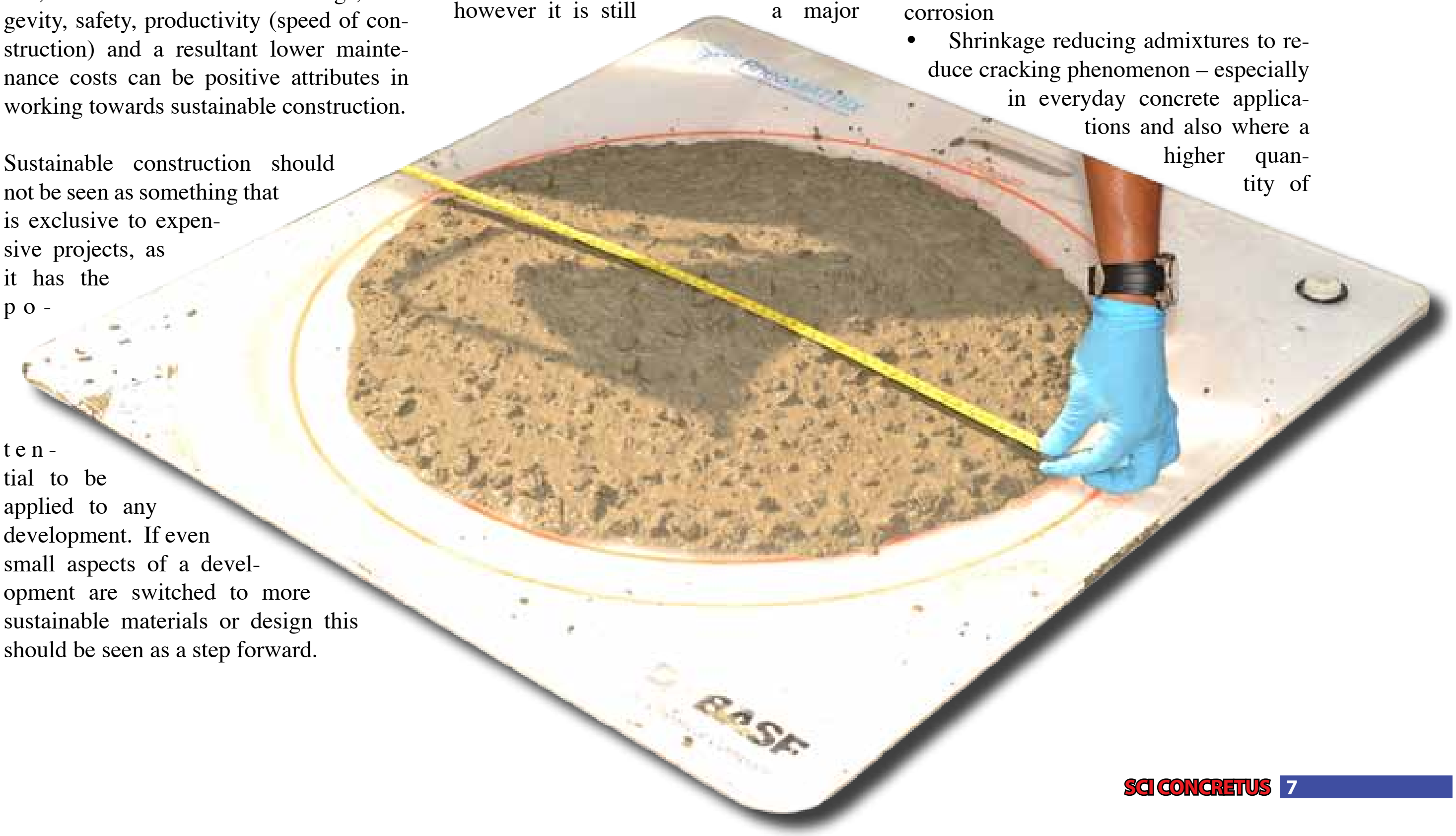
## BASF Solutions for Sustainable and Enduring Concrete

Since the focus is on implementing a few ideas to help sustainability through concrete, we will discuss the following technologies which can enhance concrete in its life-cycle performance:

- Low fines self consolidating concrete (fines < 380 kg/m3) using higher quantity of cementitious fines enabling faster placement with minimum or nil vibration.

A set of "Enduring Concrete" technologies which can be used effectively in mutually exclusive applications depending on specifications.

- Corrosion inhibiting admixtures for resistance against chloride/sulphate induced corrosion
- Shrinkage reducing admixtures to reduce cracking phenomenon – especially in everyday concrete applications and also where a higher quantity of



*Low fines self consolidating concrete in practical use*

supplementary cementitious materials are used in concrete (to guard against both plastic and autogenoeous shrinkage)

- Unique hydrophobic pore blockers for rendering concrete watertight against permeability / high water absorption (as in underground / water retaining structures)
- Superplasticizers with unique slump retaining character in concrete using higher quantity of crushed rock / manufactured / mining sand which give an assurance of safety and quality

All the above technologies have been tried and tested and provide concrete sustainability objectives.

## Low fines self consolidating concrete

Low fines self consolidating concrete having a slump flow of >550 mm at point of placement enables the following benefits:

1. Economy – savings of fines (since this is < 400 kg/m3 including supplementary cementitious materials against convention self consolidating concrete which requires 550 – 600 kg/m3 of cementitious materials); can be produced easily, ensuring faster placement / output without bleeding / segregation at high flowability levels (550 mm+); higher labour productivity.
2. Ecology - lesser cement (OPC) content ensures lower $CO_2$ impact for the given concrete and ensures higher durability by virtue of addition of more SCMs (fly ash, slag) which protects reinforcement for a longer period of time.
3. Ergonomy – almost nil vibration required (whenever the rebar spacing is > 60 mm, as is the case for the common grades of concrete C 25 – C 40) ; minimum noise generated and lower "stickiness" of concrete (ensuring smoother pumpability, thus reducing wear and tear of pump / delivery lines)

This type of concrete is now available across Asia Pacific and a significant quantity of regular grade concrete has been poured since the launch of this revolutionary concept.

Using the innovative polycarboxylate ether chemistry with a unique viscosity modifying agent it is possible to

1. have a sustainable concrete with a very good distribution of smaller air voids against irregular, larger air voids typical in common grades of conventional concrete (which we shall refer to traditional vibratable concrete)
2. favourable / reduced shrinkage data

## Other Enduring Concrete Technologies

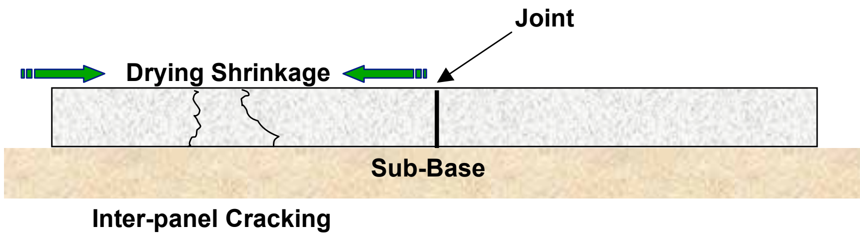
### Corrosion inhibiting admixtures

Particularly for marine structures where chloride induced corrosion are at alarming levels, corrosion inhibiting admixtures offer quite a significant durability factor to concrete structures enabling a favourable ratio of Nitrite ions to Ca++ for resistance against chloride/sulphate induced corrosion.

As an aid to the basic mix which should include supplementary cementitious materials corrosion inhibiting admixtures the new range of corrosion inhibiting admixture also helps in higher water reduction and is easy to apply. This dual role in a single product facilitates use and convenience to the end users. There are quite a number of instances where this technology has enabled use of sea sand in reinforced concrete structures, without affecting fresh or hardened properties of concrete (i.e. workability, air entrainment, setting times, strength development, length change, etc). This novel technology allows a passive membrane to form on the surface of the reinforcing steel embedded in concrete and prevents chloride ions from attacking steel and maintains a stable inhibitor condition for a long period of time.

### Shrinkage reducing admixtures

Some countries, like in Japan, have typical requirements of low shrinkage in concrete. Civil engineers and constructors have an eye for such a situation where the shrinkage in concrete (drying, plastic and autogeneous shrinkage) can be limited to within 600 x 10-6 – 800 x 10-6. Tradi-




tionally, shrinkage reducing admixtures (SRAs) have been typically known to be a separate add-on component in concrete along with normal admixtures. However, a new type of customized shrinkage reducing superplasticizer / mid range plasticizer is available – and this is based on the high performing PCE (Polycarboxylate ether) molecule chemistry.

Briefly to explain the issue on drying shrinkage, capillary tension appears to be the dominant mechanism in drying shrinkage. Stress upon drying is related to surface tension of pore water. The surface tension of pore that forms meniscus also exerts inward pulling force on the side of the pore wall. These forces in all pore sizes ranging from 2.5-50nm is the primary cause of shrinkage. Addition of SRAs lowers the pore water surface tension.

## Hydrophobic pore blockers

Special fatty acids are used in the formulation of hydrophobic pore blockers with an aim not to entrain air or reduce concrete strengths or without altering any fresh / hardened concrete property.

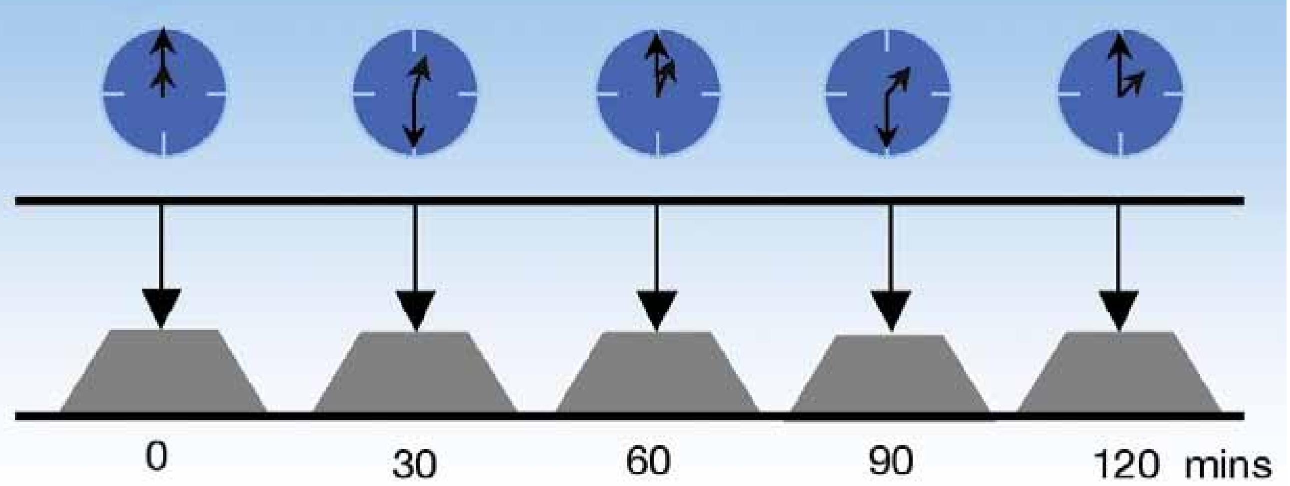
For underground structures – basements, water tanks, car parks, etc – it is essential that concrete have very low water absorption 0.8 – 1.2% (as tested as per BS 1881, Part 122 – Method of determination of water absorption in concrete) and low permeability) and low values for test against depth of water penetration under pressure which should be usually 8 – 12 mm.

Suitable proportion of supplementary cementitious materials should also be used in the mix design aided with a superplasticizer (to maximize dispersion of cementitious materials and obtain optimum water reduction) and a compatible hydrophobic pore blocker (which does not negate concrete strength).

## Superplasticizers with slump retaining capability

Quite a significant innovation has been made in modifying the new generation of PCE (polycarboxylate ethers) using a basic "toolbox" approach where various synthesized polymers (maybe referred to as "building blocks") are used in perfect blend to have a formulated PCE based superplasticer to have unique properties as desired in construction. In the major cities, traffic congestion is usual and concrete ready mix companies have the biggest challenge to ensure proper workability retention (slump or flow) at site for the contractors. Typically the slump retention maybe two to four hours. Another challenge is the depletion of natural sand sources and the increased usage of manufactured / crushed sand. Add to this the ever changing limestone benches which have an impact on cement composition. What concrete technologists look for is a robust admixture with a capability of super retention of workability.

*Super retention technology provides unrivalled quality of slump retention of concrete*




Using the above mentioned tool box technology it was possible to craft a unique product based on PCE chemistry to give super slump retention character of concrete with unaffected set times and strength. This technology was extended to be used in normal concrete grades as well as in normal to high concrete grades in Asia Pacific (25 MPa – 70MPa) both in precast as well as ready mix or site batched concrete using higher levels of cementitious materials. Use of higher levels of cementitious levels goes on to increase the longevity of a structure with higher durability criteria met.

## Conclusion

Extending the life-cycle of a construction is identified as a mega-trend of the industry, and perceived as a major factor for sustainability of society's development. Governments, societies, architects, designer, engineers, contractors and concrete producers, thus, the entire value chain are aware of the benefits of enhanced durability of buildings.

With the thrust on issues like "green", "sustainability", "sustainable construction" and last but not the least "Concrete Sustainability", it will help to realize the dreams of durability and longevity of concrete structures as more such technologies get specified and the references of use start building up.

*(L) Conventional concrete and (R) Concrete with super retention technology at 90 min elapsed time*

# IF CONCRETE CAN SPEAK
# How Green Am I?

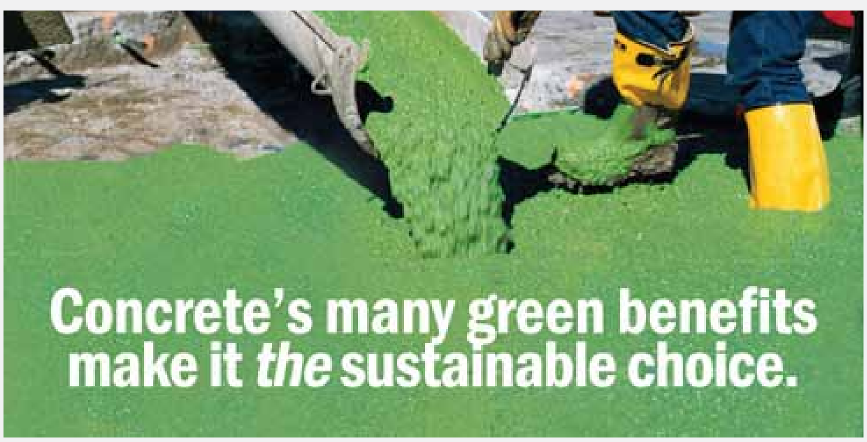
By Dr. Tam Chat Tim, Associate Professorial Fellow
National University of Singapore

In recent months, extreme weather events, floods and serious earthquakes happened in different parts of the world. Climate change is a topic on everyone's mind. However, economic development has to continue for the welfare of all and infrastructure construction is the basic unit to enable such progress. In most parts of the world concrete, that is me, remains the major material of construction. One part of me, cement has the highest carbon footprint compared to the rest of myself. To minimise my impact on global warming I need to become more and more "green"!

I am often referred to as "green" when I am at the early stage of my existence, i.e. before setting. After setting, I can stay "green" (in colour) forever, if chrome green chemical is included in me. However, it is in terms of carbon footprint that is of most concern for my being "green" in continuing economic development through concrete construction. My very existence is created by my chemically active component, cement. Nominally, the production of 1 unit mass of cement is linked to 1 unit mass of CO2. Over the years, cement manufacturers have make significant reduction in CO2 emission and today, the value is down to around 0.8 tonne CO2 per tonne of cement. This is the "cradle to gate" value. In Singapore, all cement has to be imported and the additional CO2 footprint for transport and additional handling will make its total higher. The Government has targeted a reduction of 12% in CO2 emission by 2020 on the "business as usual" (BAU) basis and 16% if there is international agreement. I need to be a contributing member to the low-carbon age. Hence, every measure should be taken to make me more "green" by minimising the amount of cement that goes into making me.

### What are these measures?

*GREEN CONCRETE - Fresh Concrete or Coloured Concrete*




*Source: www.ces.purdue.edu – L Caplan, download 3 April 2010*

### Replace, Reduce and Recycle

Although I cannot be made without cement, but there are alternate cementitious materials that can partially replace conventional Portland cement (CEM I in the new Euro nomenclature). Fly ash from the burning of coal in power generation has been available for such usage in other countries where it is available, for many decades. The use of increasing percentages of replacement has to be balanced with the full understanding of its influence on my rate of strength development. In addition, the need for adequate time of nurturing (curing) to build up the capability of the surface zone of my body to provide protection to the steel reinforcement that enables me to take tension in service. This applies also to the case of partial replacement of Portland cement with ground granulated blastfurnace slag (ggbs) generated from the smelting of iron ore. Others include microsilica and other pozzolanic materials.

The amount of cement I need to develop a particular strength, say at the age of 28 days, will be reduced to a minimum as long as the water content needed for producing me in the mixing process is at a minimum. This is limited by two factors, the mixing technology and the need to enable me to be easier formed into various shapes (consistence level in the new Euro norm or workability formerly). The former will have to wait for new generation of mixing technology to become available in normal production, although it has been developed in research. In terms of consistence, the availability of successful generations of plasticiser and super-plasticiser has enabled the water content need to produce me in the range of 140 to 160 kg/m3 in most cases. Hence, no more than 400 kg/m3 of cementitious materials are required in general for normal range of my 28-day strength.

Besides reduction in total cementitious content, designers may like to consider if the same structural element can be made to me perform with a small cross-section, by select me with higher 28-day strength. Although slightly higher cement content is often needed to make me stronger at my age of 28-days, the reduction in my size, particularly as columns, may well result in less total volume of me needed (see further reading). Hence, the final CO2 content for the element may be reduced. On the other hand, my smaller physical footprint provides more usable floor area – a positive financial benefit, besides a smaller carbon footpring.

I can be recycled in the form of RCA but I can also be recycled directly in my physical form as a structural element. This is the concept of "design for deconstruction"; when as a column or beam element, I can be harvested from an existing structure at the end of its useful life, to be reused in a new structure. Currently I am such a candidate being evaluated in an on-going research project jointly conducted by a team from the Housing and Development Board and the Department of Civil Engineering at National University of Singapore.

In the near future, I look forward to the development for the design my intended service life in different exposure conditions to be rationally carried out through performance-based durability analysis (see further reading), to replace the current "deem to satisfy" prescriptive approach, e.g. SS EN 544-1. Being more durable will make me even more "green" and more competitive as I can achieve a longer service life before needing maintenance, repair and eventual replacement.

Yes, please make me more "green"!

Further reading:

1. Challenges in Concrete for Sustainable Construction, C.T. Tam, K.C.G. Ong, M.H. Zhang MH and J. B. Hao, Keynote Paper, 10th International Conference on Concrete Engineering and Technology, CONCET '09, Shah Alam, Selangor, Malaysia, 2 – 4 March 2009.

2. Durability design and quality assurance of concrete infrastructure (Performance-based programs boost service life, Odd E. Gjørv, Concrete International, September 2010, pp29-36

# Ferrocement and Fibre-reinforced aerated pavers for open car-parks

*Dr R Sri Ravindrarajah*
*Centre for Built Infrastructure Research, University of Technology. Sydney, Australia*
*Currently: Visiting Associate Professor, Nanyang Technological University, Singapore*

Use of conventional concrete and bituminous pavements for open car park construction is now considered as environmental unfriendly due to their impervious nature. The rainfall on these surfaces is very often causing flash flood in the urban areas. Many cities are gradually losing their open-spaces due to ever-increasing demand for residential and commercial developments. In many urban cities, high intensity rain-falls within a short period of time causing flash flooding in many cities due to poor drainage. The flood situation is becoming more dangerous and costly when the drainage system is either blocked or overloaded. In order to minimise the burden on the local council drainage infrastructure, many local government authorities in NSW, Australia are enforcing the construction of on-site stormwater detention tanks in residential sites.

As a new development in concrete technology, the use of pervious concrete in the construction of car-parks and walkways are becoming popular in many countries, especially in the USA. Pioneering research at the University of Technology, Sydney was conducted on pervious concrete and the results published elsewhere [1-3].

For a number of years, precast aerated reinforced concrete pavers of different sizes and shapes are used for the construction of open car parks in Singapore. Although majority of them performed well, significant number of such pavers showed cracking and disintegration.

Ferrocement is known to have significant dimensional stability (4), watertightness (5) and crack resistance (6) and suitable to produce thin structural elements. Similarly, steel fibre reinforced cement composites are known to have significantly improved crack resistance [7]. This paper discusses the applicability of steel fibre-reinforced mortar and ferrocement to produce aerated car park pavers as an alternative to the steel reinforced pavers for open car park construction.

## Survey of aerated car park slabs

In Singapore, majority of the aerated concrete pavers used in housing estates and industrial units open car parks are reinforced concrete with 10mm diameter bars. The use of precast aerated concrete pavers provides car park with grass surface appearance and aesthetically pleasant aeration patterns. It also allows percolation of surface water into subsoil hence reducing heaving problems. However, structurally the use of aeration pavers appears to be less superior to convention concrete pavement.

### Type of aeration pavers

The main factors affecting the choice of a particular aeration pattern of the reinforced concrete pavers are aesthetic and structural requirements. The shapes of these aeration pavers are rectangular, square or hexagonal. The thickness of pavers varied between 60 to 75mm. The shapes of the voids in these pavers are rectangular, square or rounded. The aeration (or void) area content varied between 16.6% and 44.3% of the total paver area. The largest and heaviest paver used had the dimension of 735mm by 735mm by 75mm with 8 rectangular openings of 245mm by 55mm (producing the void area content of 31.6% of the total area). The approximate weight of this paver is 66.5kg. The most commonly used paver in the car parks is 735mm by 375mm by 65mm reinforced concrete with four 240mm by 50mm voids, producing 38.7% void area content. The weight of each paver is about 26.8kg and it can be easily handled by the construction workers. In this study this paver is chosen to investigate its field performance, in addition to its mechanical properties.

*Fig. 1: Deteriorated reinforced concrete pavers*

*Fig. 2: Cracked reinforced concrete pavers*

## Field Performance of Car-park Pavers

A satisfactory performance of car park requires cracks free condition during its service. A survey conducted in some old car parks showed that a number of the aerated reinforced concrete pavers cracked significantly. The main cause of the cracking is associated with the unevenness of the base. Unstable base led to tilting, settling and rocking of the pavers. Some possible causes for base instability are lack of interlocking between adjacent pavers, unsound base materials, uneven moisture distribution and presence of compressive soil at the joints. The reinforced concrete pavers are not capable of taking bending stresses and reinforcing bars are not sufficient to increase the ductility of the composite. Concrete being a brittle material and having limited tensile strength (below 3MPa), it is not surprising that some pavers showed significant cracking and deterioration.

A survey conducted in a car park showed that 473 out of 1500 pavers were cracked. The intensity of cracking in some pavers was very severe as shown in Figs. 1 and 2. Wide cracks in the pavers endanger the car park users. Further disintegration of the pavers could be expected with time. Therefore, in order to improve the serviceability of the open car park it is necessary to look for alternative car park paver design with improved crack resistance. In this study performance of steel fibre reinforced mortar and ferrocement aerated pavers were studied and their performance was compared with that for reinforced concrete paver.

## Experimental Investigation

Aerated rectangular pavers (635mm by 310mm) were made with three different materials, namely reinforced concrete, fibre mortar and ferrocement. Ordinary Portland cement was used for the production of the mortar and concrete mixtures. The composition of mortar for both fibre mortar and ferrocement was 1:2:0.50 (cement: fine sand: water), by weight. Dramic steel fibres, having the fibre length of 30mm and 0.50mm diameter, were used in producing the fibre mortar and the fibre content was 2% by volume. Ferrocement pavers had the welded wire mesh at the top and bottom of the paver with a cover of 7.5mm. For both fibre mortar and ferrocement pavers, three 5mm diameter mild steel bars were used with lateral bars at the top and bottom of the pavers. The reinforced concrete pavers had three 10mm diameter bars placed at the centre with lateral bars. The mix proportion for concrete was 1:2:2:0.50 (cement : fine sand : coarse aggregate (10mm) : water), by weight.

For each type of paver, six identical aerated pavers were cast in wooden moulds. Compaction was achieved by using a vibrating table. The pavers were demoulded after 24 hours and cured in water for 13 days. Three pavers for each type were tested under mid-point line loading over a simply-supported span of 555mm using an Instron testing machine. Mid-span deflection under the load was continuously monitored using an LVDT under increasing load. The first-crack load, ultimate load and load-deflection characteristics for the pavers were determined.

## Results and Discussion

Compressive cube strength for fibre mortar, ferrocement mortar and concrete was around 43MPa. Fibre mortar had the flexural strength of 16.7MPa compared to 6.4MPa for the ferrocement mortar and 5.8MPa for the concrete used for the reinforced concrete pavers. The modulus of elasticity for fibre mortar was 26.6GPa compared to 27.5GPa for ferrocement mortar and 27.1GPa for concrete.

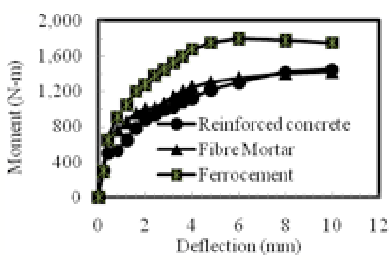



*Fig. 3: Load-deflection under flexural loading*

Fig. 3 shows the typical load-deflection characteristics for fibre mortar, ferrocement and steel reinforced slabs under flexural loading. The first-crack moment is the lowest for the reinforced concrete slab and equal to 533N-m which is similar to unreinforced concrete slabs. This shows that the 10mm diameter steel bars at the centre of paver was failed to increase the cracking moment. This is because that the steel bar was placed near the neutral axis position. Both ferrocement and fibre mortar pavers showed improved first cracking moment compared to reinforced concrete pavers. The first cracking moment for fibre mortar paver was 640N-m compared to 535N-m for steel reinforced concrete paver. Ferrocement paver showed the first-cracking moment of 625N-m. Therefore, fibre mortar pavers resisted significant moment before developing any cracks.

Considering the ultimate moment, the highest moment of 1665N-m was recorded with ferrocement pavers compared to about 1470N-m for both fibre mortar and reinforced concrete pavers. Ferrocement having increased crack resistance showed 2.66 times the first-cracking moment until the ultimate failure was occurred. The corresponding values for reinforced concrete and fibre mortar pavers are 2.31 and 2.75, respectively. Since, 10mm mild steel bar was used in reinforced concrete pavers, it had contributed to a comparable ultimate moment capacity.

Fig. 3 also shows that the ferrocement pavers has the highest fracture toughness compared to other two types of slabs. Even though the first cracking moment is important, from the point of view of the energy required to fail the pavers, the fracture toughness is equally important. Considering these two in addition to deflection control, it can be said that ferrocement pavers provide an effective alternative to the reinforced concrete pavers.

Fig. 4 shows the crack patterns for all three types of slabs under flexural loading. The fibre mortar and reinforced concrete slabs had a clean single major crack after sustaining significant deflection under flexure. The ferrocement paver showed multiple cracking and narrower crack width compared to other two paver types.

Considering the performance of these three types of pavers, it can be said that the ferrocement paver seems to be the best alternative in improving serviceability through crack control. The steel fibre mortar pavers showed comparable performance with reinforced concrete pavers. Considering the possibility of corrosion of steel fibres, this

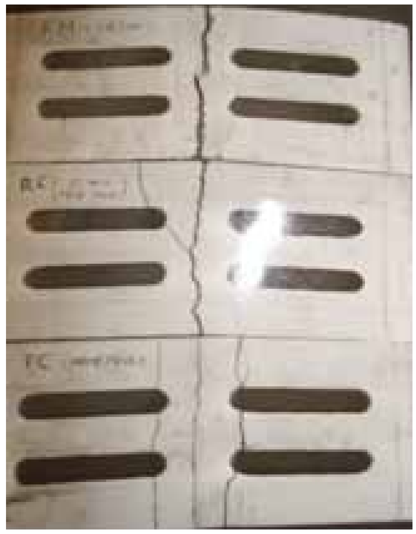


*Fig. 4: Cracking pattern of fibre mortar, reinforced concrete and Ferrocement pavers*

may not be a good alternative. In addition, steel fibres if exposed may cause harm to the car tyres and car park users.

## Concluding Remarks

Aerated car park pavers made from cement composites, namely seel fibre-reinforced mortar, ferrocement and steel reinforced concrete are tested under flexure to failure. The voids in the pavers are capable of allows the percolation of surface water. Traditional use of reinforced concrete pavers with nominal steel reinforcement is found to get damaged due to the instability of the sub-base. This investigation shows that ferrocement pavers are superior from the load carrying capacity, crack resistance, deflection and cracking pattern. With proper adoption of production technology, it is possible to produce precast ferrocement car park slabs without any difficulties.

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# Beneficiation of Recycled Concrete Aggregates

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Recycled concrete aggregates (RCA) are produced through a series of crushing, sorting and sieving operations. The end product, depending on the size range, may comprise one or more particles of natural coarse aggregate held together and surrounded fully or partially by a layer of mortar (Figures 1a and 1b) or essentially lumps of mortar (Figure 1 c) with varying proportions of fine and smaller size coarse aggregates. The former is refered to as Type I RCA particles and the latter, Type II RCA particles. . There is as-yet no practical method available to separate the two types of aggregates economically. It is common to encounter both types of RCA aggregate particles in a batch of single sized RCA.

The presence of mortar in RCA has been identified as the most important factor contributing to lowering the quality of recycled concrete aggregates [1]. The results of an experimental study conducted to investigate the effects of the total amount of mortar present on the water absorption and bulk specific density of typical RCA samples are shown in Figures, 2 and 3, respectively [2]. The samples tested comprised both types of RCA particles. As can be seen, an increase in the mortar content of RCA results in an almost linear decrease in the bulk specific gravity and increase in the water absorption.

A number of RCA beneficiation methods have been recently proposed to enhance the quality of RCA by reducing the total amount of mortar present. Such methods rely on one or more combinations of mechanical, thermal and chemical treatments to remove the mortar. In the following sections, various previously proposed RCA beneficiation methods as well as a novel microwave-assisted RCA beneficiation technique recently developed at National University of Singapore are described and compared experimentally.

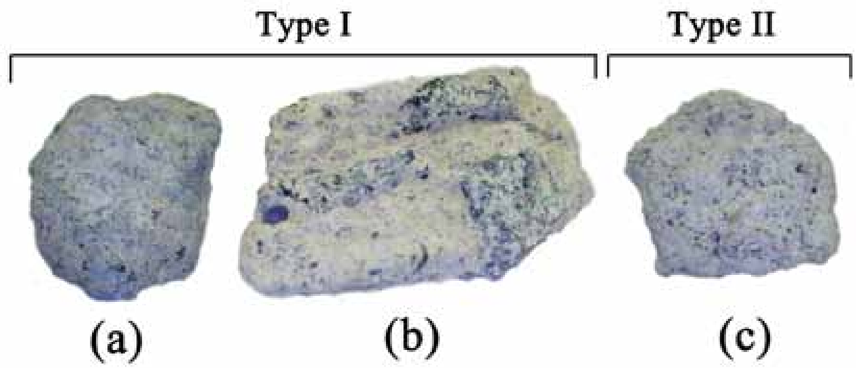



*Fig.1. Various types of RCA comprising (a) a granite particle surrounded by adhering mortar, (b) three granite particles held together and surrounded by mortar, (c) only mortar*

## RCA Beneficiation Techniques

### • Conventional Heating (Thermal Beneficiation)

In this method, RCA particles are heated at about 500 °C for about two hours. The thermal stresses generated through thermal expansion are used to fracture and thereby remove the mortar present. Moreover, according to Shima et al. (2005) when concrete is heated at temperatures higher than 300 °C, mortar is made brittle due to dehydration; lowering its resistance against the thermal stresses developed [3]. It is believed that saturating the mortar before heating can increase the efficiency of this method because it can lead to pore pressure development which may result in the faster removal of mortar. It has also been reported that immersing the heated RCA aggregates in cold water immediately after heating can lead to higher mortar removal yields through increasing the differential thermal stresses developed.

### • Mechanical Beneficiation

In this technique, mechanical forces are used to grind and remove the mortar. Two techniques have been proposed in Japan; eccentric-shaft rotor [4] and mechanical grinding [5]. In the eccentric shaft rotor method, crushed concrete lumps are passed downward between an outer cylinder and an inner cylinder that rotate eccentrically at a high speed to separate the coarse aggregate from the mortar through grinding. In the mechanical grinding method, a drum is partitioned into a number of small compartments. The mortar portion of the RCA is removed through rubbing against the iron balls placed in the compartments of the rotating drum.

### • Thermal-Mechanical Beneficiation

In this method a combination of the thermal stresses generated through conventional heating at temperatures from 300 °C to 500 °C and the mechanical stresses generated through rubbing is used to remove mortar from the RCA particles. In 1999, Shima et al. proposed a thermal-mechanical RCA treatment technique known as "heating and rubbing" [6]. In this technique, concrete debris are first heated at 300 °C in a vertical furnace to render the cement paste brittle due to dehydration. To remove the mortar, the heated concrete debris are fed into the rubbing equipment. In the equipment, the heated concrete is rubbed against steel balls and the mortar portion that is dislodged is discharged through the screening system provided. Inventors of this method claimed that it can increase the quality of RCA to comply with the JCI (Japan Concrete Institute) standards for high quality recycled concrete aggregates.

### • Acid Soaking Beneficiation

More recently, Tam et al. (2007) proposed a new method to remove the mortar by pre-soaking RCAs in 0.1 molar acidic solutions for 24 hours [7]. Three different acidic solutions (HCL, $H_2SO_4$, $H_3PO_4$) were considered in this study. They reported that the water absorption of RCA after treatment reduced, showing improvements in the range of 7.27% to 12.17%. A major drawback of this method is the increase in the chloride and sulfate content present in the RCA aggregates respectively after treatment with hydrochloric and sulfuric acids. The increase in the chloride and sulfate content present may pose serious durability issues.

### • Chemical-Mechanical Beneficiation

Abbas et al. (2008) proposed to use combined chemical degradation through exposure of RCA to sodium sulfate solution and mechanical stresses created through subjecting RCA to freeze-and-thaw action to separate mortar from RCA [8]. However, the main objective of their study was focused on quantifying the amount of mortar present for use in RCA classification. The technique "as is", is not suited for full scale RCA production.

### • Microwave-Assisted Beneficiation

A novel microwave-assisted RCA beneficiation technique has been developed recently at the National University of Singapore. This method takes advantage of the differences in electromagnetic properties and water absorption of natural aggregates and mortar to heat them at considerably different heating rates. The differential heating of natural aggregates and mortar may lead to development of high differential thermal stresses within the mortar, especially at its interface with the embedded natural aggregate. The differential thermal stresses developed are harnessed to break up and separate the mortar without damaging the natural aggregates. To achieve better efficiency and yield, the microwave frequency, microwave power and water content of the RCA samples to be treated may be optimized.

It is noteworthy that compared to conventional heating, microwave heating is significantly more energy efficient because it volumetrically heats up only the RCA exposed to it, not the entire heating chamber together with its contents. The efficiency of microwave heating in the current state of art systems reported may be as high as 90%. The microwave-assisted RCA beneficiation requires significantly shorter duration (a few minutes) compared conventional heating technique (120 minutes). This leads to significantly lower energy consumption compared to conventional heating beneficiation methods. In addition, the maximum temperature reached by the RCA particles during the microwave assisted RCA beneficiation method is only about 200 °C. Due to the shorter heating duration and the lower temperatures reached compared to conventional heating mthods, the quality of the original coarse aggregates, e.g. granite is more likely to remain unaffected after processing.

## Experimental Program

### • Materials

To produce RCA, 40 day old laboratory-cast concrete specimens were crushed in a jaw crusher. According to available literature, the properties of RCA change with the particle size. Hence, in order to eliminate the effects of RCA size, the RCA particles belonging to the 8-12 mm size fraction were used throughout this experimental study. Since, there is as-yet no practical methods to separate and remove Type II RCA particles, both types were present in the samples tested. On average, 17% of the total RCA particles in the samples tested (8-12 mm) were Type II RCA, comprising only mortar while the rest were comprised of one or more granite particles held together and partially or fully surrounded by mortar. The 24-hr water absorption, bulk density (OD) and total mortar content of the RCA samples were, on average, 4.2%, 2370 kg/m3, and 47% (by mass), respectively. The bulk density (in oven-dry condition) and 24-hour water absorption of the natural coarse aggregates used in original concrete were 2580 kg/m3 and 0.6, respectively.

### • Experimental Methodology

The methodology used in this study is described in the following sections.

***Conventional Heating Beneficiation (Thermal Beneficiation)***

Saturated RCA samples (2 kg oven dry weight) were heated in a conventional furnace for 2 hours. Two different heating temperatures of 300 °C and 500 °C were used. After heating, the RCA samples were immediately cooled down by immersing in a water tank filled with 25 °C water.

***Mechanical Rubbing Beneficiation***

Los Angles abrasion testing equipment with a load of 10 steel balls was used to rub the RCA samples (10 kg oven dried weight) against each other and the steel balls for 100 revolutions of the rotating drum.

***Thermal-Mechanical Beneficiation***

RCA samples were heated at 500 °C as in the thermal beneficiation technique. 10 kg (oven dried weight) batches of heated RCA were then rubbed using the Los Angles abrasion testing equipment as in the mechanical rubbing beneficiation technique.

***Acid Soaking Beneficiation***

2 kg oven dried samples were placed into a plastic container which was then filled with the acid solution, diluted to the desired concentration. The samples were soaked for the specified duration and were then washed on a 4 mm sieve to remove the detached mortar and acid. Three sulfuric acid concentrations of 0.1, 0.5 or 1 molar at two soaking durations of 1 day or 5 days were considered.

***Microwave-Assisted RCA Beneficiation***

A pilot industrial microwave-assisted RCA beneficiation system capable of operating continuously at 10 kW power installed in the Structural Engineering Laboratory of the Department of Civil Engineering, National University of Singapore (Fig. 4.), was used to heat 2 kg (oven dried weight) RCA samples for 1 minute. After heating, the samples were immediately cooled down by immersing in 25 °C water. To examine the effects of the RCA water content, RCA samples with two different initial moisture conditions were considered; 1) Air-dried (AD): two kg oven dried RCA samples were immersed in water for 24 hours and were then kept at room temperature conditions for 21 days; 2) Saturated (SA): Air-dried RCA samples were immersed in water for 24 hours.

***Microwave Heating and Mechanical Rubbing***

To investigate the efficiency of combining the microwave heating and mechanical rubbing treatments, 10 kg batches of the saturated RCA were microwave heated as in the microwave-assisted beneficiation technique and were then rubbed using Los Angles abrasion testing equipment as in the mechanical rubbing technique.

## Results and Discussion

The results of an experimental study conducted to compare the efficacy the various beneficiation methods are presented in Table 1.

As previously showed in Figures 2 and 3, there is an almost linear relationship between the total mortar content and the water absorption and bulk density of the RCA samples. Hence, in the following discussion, total mortar content will be used as the basis for comparison between various RCA beneficiation techniques.

As can be seen in Table 1, results showed that while a single run of microwave heating resulted in almost 48% reduction in the mortar content of RCA, conventional heating at 300 °C and 500 °C reduced the mortar content by only about 6.4% (from 47% to 44%) and 12.8% (from 47% to 41%), respectively. This is mainly because microwave heating leads to a faster and more concentrated heating of mortar, resulting in higher differential thermal stresses developed in the mortar (especially at the ITZ), whereas conventional gradually heats up the entire RCA particle, granite

| Beneficiation Process | | | Process Duration (hr) | Properties of RCA | | |
|---|---|---|---|---|---|---|
| | | | | 24-hr Water absorption (%) | Bulk density (OD) (kg/m$^3$) | Mortar content (%) by mass |
| Before Beneficiation | | | | 4.2 | 2370 | 47 |
| Single-Stage Processes | Microwave Heating | Pre-saturated RCA | ~ 0.02 | 2.8 | 2460 | 24 |
| | | Air dried RCA | ~ 0.02 | 3.4 | 2430 | 32 |
| | Conventional Heating | 300 °C | 2 | 4.1 | 2380 | 44 |
| | | 500 °C | 2 | 3.8 | 2390 | 41 |
| | Mechanical Rubbing | | ~ 0.1 | 3.5 | 2410 | 34 |
| | Acid Soaking | 0.1 Molar sulfuric acid | 24 | 4.1 | 2380 | 45 |
| | | | 120 | 4.1 | 2380 | 45 |
| | | 0.5 Molar sulfuric acid | 24 | 3.9 | 2390 | 41 |
| | | | 120 | 3.4 | 2420 | 33 |
| | | 1 Molar sulfuric acid | 24 | 3.5 | 2410 | 34 |
| | | | 120 | 1.6 | 2500 | 13 |
| Combined Processes | Conventional Heating and Mechanical Rubbing | 300 °C | ~ 2.1 | 3.3 | 2430 | 31 |
| | | 500 °C | ~ 2.1 | 2.1 | 2480 | 21 |
| | Microwave Heating and Mechanical Rubbing | Pre-saturated RCA | ~ 0.12 | 1.1 | 2550 | 7 |

*Table 1. Properties of RCA before and after treatment using various beneficiation techniques*

and mortar, to the same temperature. The magnified surface of an individual Type I RCA particle before and after microwave heating is depicted in Figure 5.

The results presented in Table 1 also revealed that soaking the RCA particles in a 0.1 molar sulfuric acid solution as proposed by Tam et al. (2007) reduced the mortar content by only about 4%. Significantly higher improvements in the RCA properties (up to 72% reduction in the mortar content) were achieved using the higher acid concentrations (0.5 and 1 molar) and longer soaking durations. However, such high acid concentrations are significantly more hazardous when used on an industrial scale. Moreover, the use of concentrated sulfuric acid may considerably increase the sulfate content present in the RCA after beneficiation which in turn would give rise to durability concerns. Moreover, acid soaking is too time consuming, taking at least 24 hours overall. Hence, acid soaking at high acid concentrations may only be considered as an efficient test method to obtain the mortar content of small samples of RCA in the laboratory.

Compared to conventional heating and acid soaking methods, slightly more promising improvements were achieved using the mechanical rubbing technique. The results showed that 100 revolutions of mechanical rubbing using the Los Angles abrasion testing machine with 10 steel balls inside the rotating drum reduced the mortar content of RCA by almost 28% (from 47% to 34%). Intuitively, the removal of mortar is likely to be proportional to the number of steel balls used, the volume of the material rubbed and number of rotations of the drum. A Tradeoff between the quality of the RCA, the processing time and the energy consumption is necessary. When compared to microwave heating, mechanical rubbing requires significantly longer processing time and energy to achieve a similar yield and quality and thus may not be an economical option in practice. Furthermore, mechanical rubbing is the noisiest technique among all the beneficiation methods discussed.

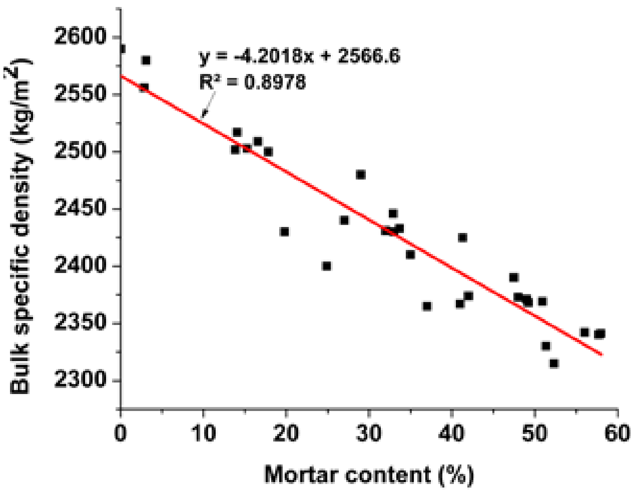



*Fig.2. Relationship between mortar content and water absorption*

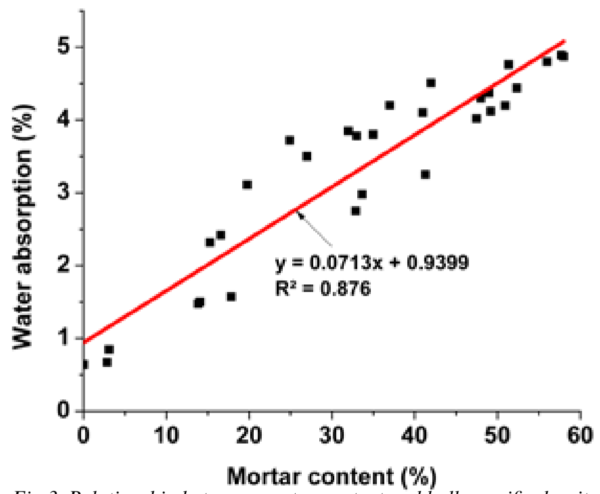
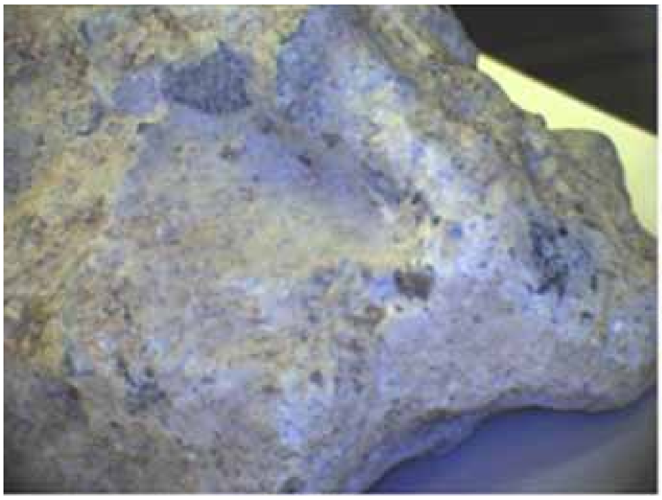



*Fig.3. Relationship between mortar content and bulk specific density*



A RCA particle before beneficiation

Same particle broken into three pieces after microwave heating

*Fig.5. Surface of a RCA particle before and after microwave heating*

In addition, results showed that combined "conventional heating and mechanical rubbing" technique resulted in almost 34% (from 47% to 31%) and 55% (from 47% to 21%) reduction in the total mortar content of RCA when heating temperatures of 300 °C and 500 °C were used, respectively. These are more than 4 times better than that achieved using conventional heating alone, suggesting that there was weakening of the mortar after heating. However, the reduction in the total mortar content achieved using the combined "conventional heating and rubbing" were about 30% less than that achieved using the combined "microwave heating and rubbing" technique, confirming that microwave heating is more efficient.

## Conclusions

Results confirmed that microwave heating may be effectively used to partially remove the cementitious mortar through developing high temperature gradients and thus high thermal stresses within the mortar, especially at the interfacial zone with the natural aggregates. Also, the results showed that saturating the RCA particles prior to exposure to microwaves can significantly increase the yield and quality of the RCA produced.

Shorter processing time compared to acid soaking and combined chemical-mechanical beneficiation methods and less energy consumption in comparison with the conventional heating and mechanical rubbing methods are among the advantages of the microwave-assisted beneficiation. The latter is also not prone to durability concerns associated with the acid pre-soaking method.

## Acknowledgements

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*Fig. 4. The pilot microwave heating system designed and fabricated for use in the experimental program, (a) Microwave generator unit (b) RCA beneficiation chamber.*

# concrete products

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Along with the traditional transit time and pulse velocity measurement, Pundit Lab offers path length measurement, perpendicular crack depth measurement and surface velocity measurement.

Optimized pulse shaping gives greater transmission range at lower voltage levels. This coupled with automated combination of the transmitter voltage and the receiver gain ensures an optimum received signal level, guaranteeing accurate and stable measurements.

The Windows based software Pundit Link unlocks the full capabilities of the Pundit Lab providing online data acquisition to reduce the testing time significantly. With the Pundit Link the user is able to view and analyze the received waveform on the PC. The measured data can also be viewed on a connected oscilloscope. Moreover, full remote control of the instrument, including data logging, is possible via a USB connection.

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# Investigation, remedial Recommendations and finite element analysis for delamination problems on a façade

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A condition assessment of the façade of a commercial building was carried out through a desktop review and detailed investigation. The principal problem reported was delamination of the mosaic tile and render layers from the precast concrete cladding panels forming the façade. The detailed investigation programme involved i) field testing consisting of delamination survey, in-situ bond strength tests and extraction of core samples, ii) chemical analysis to determine mix composition, iii) petrographic examination of tile/render/concrete layers and iv) infra-red thermal imaging survey.

About 15% of the façade area was found to be delaminated indicating the build-up of stresses induced due to differential expansion/contraction within the underlying layers of the façade. Low bond strength and areas of thermal anomalies were reported at some locations. Many occurrences of the delaminated areas were adjacent to the expansion joints between the precast concrete panels reflecting the inability of the tile and render finishes at the joint to accommodate movement.

To alleviate the above concerns, the application of a protective system was proposed after repairs to the delaminated areas and the expansion joints. This system involves i) anchoring of the façade to strengthen the composite layers and ii) fixing of a mesh and binder to act as a holding layer for the existing tiles. Finite element modeling and analysis of the proposed system was carried out to evaluate its effectiveness. Analysis was carried out under different loading regimes comprised of gravity and wind loads. The resistance offered by the repair system was found to be adequate enough to resist the maximum pull-out and shear forces anticipated on the façade in the event of future delamination.

## Description of Façade System

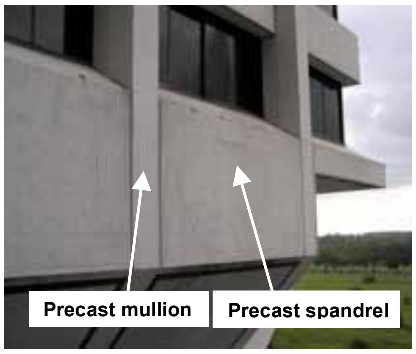


*Figure 1 View of precast spandrel and mullion*

The façade consists of precast concrete elements that are connected to the structural frame using mechanical steel bolts and nuts and grouting the bolt holes with cementitious grout. The horizontal façade component is termed "spandrel" while the vertical façade component is termed "mullion". A typical spandrel is about 13 feet in length and 6.5 feet in height whereas a typical mullion is about 2 feet in length and 11.5 feet in height. There are movement joints between two mullions with butyl rubber as the sealant and tooling material and polyurethane foam as the backing material. The joint between the mullion and the spandrel is sealed with non-shrink waterproof grout. A typical photograph of the spandrel and mullion can be seen in Figure 1. Figure 2 provides a view of the mullion-to-mullion joints and mullion-to-spandrel joints on the façade.

## Close-up Inspection of the Façade

A preliminary visual inspection was first conducted to ascertain the types, extent and severity of the various defects observed on the façade and also to select a suitable location for the close-up inspection. The preliminary visual inspection revealed spalling of the mosaic tiles and/or render at several locations on the facade. Hairline cracks and staining on the façade as well as deterioration of the sealant at movement joints were also visually evident. However on the whole, the preliminary visual inspection did not show distress areas requiring immediate attention.

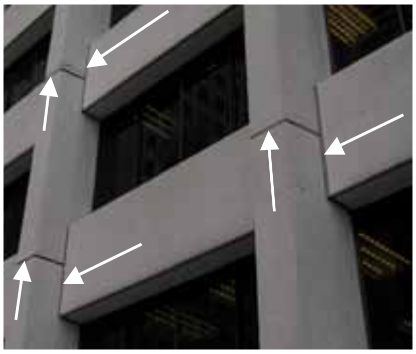

*Figure 2 Movement joints on the tiled façade*

A portion of the façade covering the width between two mullions on the façade was chosen for close-up inspection on each elevation. The choice of the locations was made based on the results of the preliminary visual inspection and the history of defects observed. The important observations noted during the close-up inspection were:

a) Moderate to severe deterioration in the condition of the sealant on the movement joint between the mullions and on the joint between the window sill to the tiled façade was observed. There was widespread crazing of the sealant material. At some locations, the failure of the sealant at the interface between sealant and the substrate ("adhesive failure") whereas at some other locations the sealant had failed within itself ("cohesive failure"). This can be seen in Figure 3.

b) At several locations, rows of mosaic tiles adjacent to where the spandrel meets the mullion were noted to have spalled. Further at some of these joints, water could have penetrated the façade as there was evidence of previous repairs by application of a sealant over these areas.

c) Several of the corner joints where the sloping face of the spandrel meets the vertical face were noted to have cracked up resulting in a gap. The cracks and the resultant gap are formed possibly due to the

*Figure 3 Spalling of mosaic tiles on precast mullion*


*Figure 4 Adhesive and cohesive failure of the sealant*

high stress concentrations of the precast spandrel at that location.

d) Fine hairline cracks were noted randomly over the tiled façade, these cracks are likely to have occurred due to shrinkage of the render substrate with no significance to the integrity of the building structure.

A hollow sounding survey was carried out during the close-up inspection to identify delaminated and de-bonded areas on the façade. The delamination was found to be of 3 types – i) between tile and tile adhesive, ii) between tile adhesive and render and iii) between render and concrete. In general, the extent of render delamination on the sloping face of the spandrel was higher than on the vertical face. Delamination was noted to have occurred commonly at areas above and below the movement joint between 2 mullions at several locations. The extent of hollow sounding area was estimated to be about 15% of the total tiled surface area.

## Results from Experimental Testing

### Adhesion Strength of Composite Layers

On each elevation of the façade, 6 nos. of adhesion strength (pull-off) tests were selected on sound areas (non-hollow sounding) areas. The tests were carried out based on a procedure adopted from ASTM C482-02 [1] and ASTM D4541-02 [2]; the selection criteria were based to achieve an even distribution of test points to cover the low, medium and high floors of the building. The tests results revealed the following:

a) About 25% of the test points failed at the interface between the render and concrete with a median adhesion strength value of 0.44 N/mm2 and an average value of 0.49 N/mm2. This adhesion strength can be considered to be reasonable based on the Singapore Housing and Development Board Specification for Building Works [3] which stipulates a value of 0.4 N/mm2 for good render to concrete bond.

b) About 71% of the test points failed within the render itself with a median adhesion strength value of 0.17 N/mm2 and average value of 0.34 N/mm2. This adhesion strength is considered to be generally low.

c) 1 no. of test point failed between at the interface between the tile and tile adhesive

### Composition and Quality of Composite Layers

Four samples (1 from each elevation) for determination of the cement to sand ratio within the render layer. The results of the cement to sand ratio ranged from 1:2.4 to 1:3.2 indicating a fairly consistent composition around the commonly specified cement-sand ratio of 1: 3.

Petrographic analysis of one sample was carried out based on a procedure adopted from ASTM C856-04 [4]. The microscopic examination revealed that the sample comprised of a 3.8mm thick external mosaic tile (with a 20mm x 20mm surface area for each tile grid), followed by a layer of outermost light cream coloured render layer thickness averaging 9.7mm and an inner grey-fish coloured render layer of thickness averaging 9.0mm. Lenticular voids between the tiles and outermost cream coloured render and also between the outermost cream coloured render and innermost grey coloured render were noted. Further the sample de-bonded at the interface between the render and the hardened concrete substrate during the core extraction process

### Infra-Red Thermal Imaging

An infra-red thermal imaging survey of the entire façade was carried out to detect areas of thermal anomalies on the façade and correlate them with the defects observed; the method of the survey was based on ASTM C1060-90 (2003) [5]. The thermal imaging was performed usually in the late morning to evening periods to ensure that the surfaces received sufficient heating from the sun thereby providing sufficient intensity of radiation for accurate thermal mapping. Based on temperature differences, correlations were made to identify areas of delamination as well as areas of water ingress into the façade. In general, the occurrence of anomalous images was more frequent on the sloping face of the spandrel and on the edge between the sloping and vertical face of the spandrel; this was in tune with the findings from the close-up inspection. Though not entirely accurate, the thermal mapping served to provide some guidance for identification of the areas with occurrence of defects over the entire façade;

## Discussion on Condition of the Façade

### Delaminated and Spalled Tile Areas

The tile delamination and spalling are a consequence of thermal movements within the underlying layers of the façade as well as low adhesion within the render layer. There is continuous expansion / contraction of the composite layers of the façade due to weathering and atmospheric heating and cooling effects. The rate (and hence amount) of movement between the various underlying layers is different as each has different thermal expansion properties. Delamination can possibly occur due to the stresses and movements induced due to such differential expansion /contraction of the various layers. These stresses and movements continue over the service life of the building with the extent of such delamination generally increasing with age. It is hence necessary to undertake suitable remedial action before the resulting spalling of tiles and/or render becomes very widespread and causes major safety concerns.

Secondly, the findings from the adhesion strength tests where about three-fourths of the samples failed within the render layer at generally lower than expected values seem to indicate the inconsistency of workmanship quality during application of the render.

### Water Penetration

The ingress of water has occurred principally through the deteriorated sealant joints of the façade. The cracking/hardening and crazing observed on the sealant seem to be primarily due to gradual wear and tear with age. The occurrence of adhesive failure at the interface between the sealant and its substrate may additionally be due to incorrect joint geometry/design and/or poor installation of the sealant. In such cases, the joints have not been able to accommodate the required movement leading to an earlier than expected failure.

## Remedial Recommendations

The rehabilitation solution for the façade was hence designed to suitably address the issues of delamination and water ingress discussed above. Further the disruption and disturbance to occupants and operations within the building needed to be kept to a minimum.

Firstly large delaminated areas were proposed to be marked out, cut at the boundary and hacked off. This would be followed by proper surface preparation and reinstatement of the hacked area with proprietary external renders.

To prevent future delamination, strengthening of the façade by improving the bond between the composite layers of the façade through the installation of anchors was recommended. The anchors would be fixed into the concrete substrate. In addition to the mechanical strength provided by the anchoring, epoxy resin would be filled into the drilled holes to bond the composite layers together by additional chemical action. The spacing between the anchors and depth of the anchors into the concrete substrate would be based on the design calculations to resist the loads from the composite layers.

Subsequent to the strengthening, the façade was proposed to be covered with a fibreglass mesh in an epoxy or cementitious resin binder layer. The purpose of the mesh was to hold back loosely adhering tiles (if any) after washing of the tiled façade with a high pressure water jet and prevent the tiles from falling off in the future. The mesh would be secured to the installed mechanical anchors at pre-determined spacings. Following this, a skim coat/fairing coat would be applied to level the tiled façade to receive the architectural finish. Finally the application of a suitable architectural finish then would provide the desired aesthetic finish to the façade.

Repair of the movement joints on the façade requires a proper understanding of the joint geometry and design i.e. the correct depth-to-width ratio and the type of sealant material to be used. The repair procedure recommended was fairly straightforward and involved the removal of the existing sealant and backing material, cleaning, surface preparation of the joint and reinstatement with new sealant and backing material. However, appropriate quality control testing and supervision is necessary to ensure a good quality of workmanship.

## Finite Element Modelling and Analysis

In order to assess the performance of the anchor-mesh-binder system of the successful tenderer, a finite element modelling and analysis of the system under different loading scenarios was carried out. The model represented a vertical flat laminated surface with no boundary disruptions, representing an internal condition, remote from edges and/or joints. The surface area of the façade panel for modelling was taken as 1.2m x 1.2m. The properties and dimensions of the components of the repair system are given in figure 5. For the modelling, the basic applied load cases were:

1. Material Self-weight
2. Wind Suction of 1.5 kN/m2 (a conservative estimate of the design wind loading for a 40 storey building in Singapore)

Load combinations of 1 (self weight) and 1+2 (self weight and wind suction) were applied to 2 debonding scenarios on the façade:

Scenario 1 : Total debonding between render layer and concrete substrate.

Scenario 2 : Total debonding between mosaic tiles and mesh/binder layer

The choice of the full debonding scenarios represents an extreme case and ensures that maximum loading is applied to the anchors and repair system. In the case of partial debonding, some proportion of applied self-weight and wind suction would be transferred directly to the underlying concrete and render structure, thereby reducing the forces applied to the repair system compared to the fully debonded scenarios, together with resultant deflections.

| Material | Properties |
|---|---|
| Anchor with epoxy resin | Pull-out load for 30 mm embedment (when grouted with epoxy resin) : **2500 N** (before applying the recommended safety factor of 4)<br>Tensile load for 30 mm embedment (when grouted with epoxy resin) : **1770 N** (before applying the recommended safety factor of 4)<br>Spacing of anchors : **600 mm** |
| Fibreglass Mesh | Thickness : **2 mm**<br>Density : **15.7 $kN/m^3$**<br>Maximum Tensile Stress : **1.85 $N/mm^2$**<br>Maximum Strain : **5%** |
| Cementitious Binder | Thickness : **3 mm** on either side of the mesh<br>Density : **24.0 $kN/m^3$**<br>Maximum Tensile Stress : **2.8 $N/mm^2$**<br>Maximum Compressive Stress : **25.0 $N/mm^2$** |

*Figure 5 Material properties of components of repair system*

The modelling and analysis for this system was done using the Finite Element Analysis Software STRAND7. A screenshot of the model can be found in figure 6. For each case, the maximum pull-out and shear force as well as deflection at a few representative points on the modelled panel were computed.

### Scenario 1

This scenario analyses the full debonding of the mesh and binder layers from the underlying mosaic tiles layer. In the event of such total debonding, the entire load of the debonded layers is hence carried by the anchors. Figure 7 shows the deflection contour diagram for this scenario when the load combination 1+2 (self weight and wind suction) is applied. The maximum deflection from either self weight or combined self-weight and wind suction was obtained as 0.71 mm at a point (E) centrally located between the four anchors and 0.50 mm at points (A, B, C and D) located midway between pairs of anchors. The maximum anchor pullout force and the maximum anchor shear force were obtained as 540.0 N and 64.2 N respectively. The mesh was found to develop a maximum tensile force of 0.2 N/mm width of mesh in most locations.

### Scenario 2

This scenario analyses the full debonding of the mesh, binder, mosaic tiles and render layers from the underlying concrete substrate. In the event of such total debonding, the entire load of the debonded layers is hence carried by the anchors. Figure 8 shows the deflection contour diagram for this scenario when the load combination 1+2 (self weight and wind suction) is applied. The maximum deflection from either self weight or combined self-weight and wind suction was obtained as 0.02 mm at all locations. The increased thickness of the combined layer and hence increased stiffness resulted in significantly smaller deflections than in Scenario 1. The maximum anchor pullout force was obtained as 540.0 N whereas the maximum anchor shear force was found to be 272.8 N, reflecting the increased debonded mass being supported by the anchors. The mesh sustains negligible tensile force in most locations for this case.

### Evaluation of Repair System

The maximum pull-out force obtained from either scenario is 540 N. The unfactored pull-out load for the anchor when grouted with epoxy resin (for 30 mm embedment) is 2500 N (see table 1). Using the recommended safety factor of 4, the factored pull-out load becomes 650 N which is more than the maximum pull-out force of 540 N. Similarly the maximum shear force obtained from either scenario is 272.8 N. The unfactored shear load for the anchor when grouted with epoxy resin (for 30 mm embedment) is 1770 N (see table 1). Using the recommended safety factor of 4, the factored shear load becomes 442.5 N which is more than the maximum shear force of 272.8 N. Hence the proposed repair system provides adequate resistance against the maximum expected loading on the façade layers.

## Conclusion

The results of an investigation of the façade of a commercial building and its proposed rehabilitation have been presented in this paper. A detailed investigation comprising of a close-up inspection and experimental testing was first carried out to determine the nature, extent and severity of the problems and defects observed on the façade. The principal problem reported was delamination of the mosaic tile and render layers from the precast concrete cladding panels forming the façade. The information obtained from this investigation and the inferences drawn on the condition of the façade was used to develop and design the method of rehabilitation address the major defects and problems associated with the façade. Finally finite element modelling and analysis was carried out to provide a quantitative assessment of the performance and effectiveness of the proposed repair system. The results from this exercise showed that the resistance offered by the repair system was well adequate to resist the anticipated loading on the façade in the event of future delamination.

### References

[1] ASTM C482-02, Standard Test Method for Bond Strength of Ceramic Tile to Portland Cement, American Society for Testing and Materials, 2002.
[2] ASTM D4541-02, Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers, American Society for Testing and Materials, 2002.
[3] Standard Specifications for Building Works and other Installations, Housing and Development Board Singapore, 2001.
[4] ASTM C856-04, Standard Practice for Petrographic Examination of Hardened Concrete, American Society for Testing and Materials, 2004.
[5] ASTM C1060-90 (2003), Standard Practice for Thermographic Inspection of Insulation Installations in Envelope Cavities of Frame Buildings, American Society for Testing and Materials, 2003.

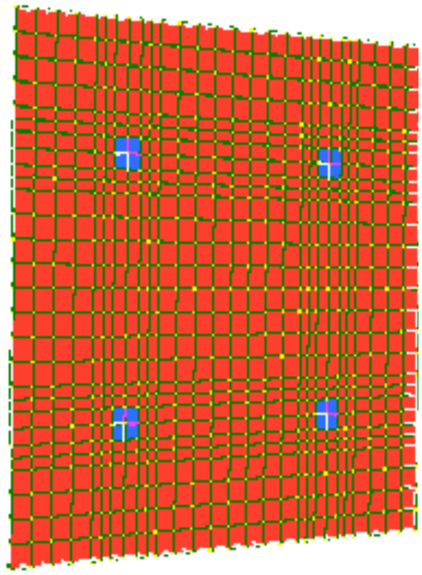

*Figure 6 Snapshot of model of repair system*

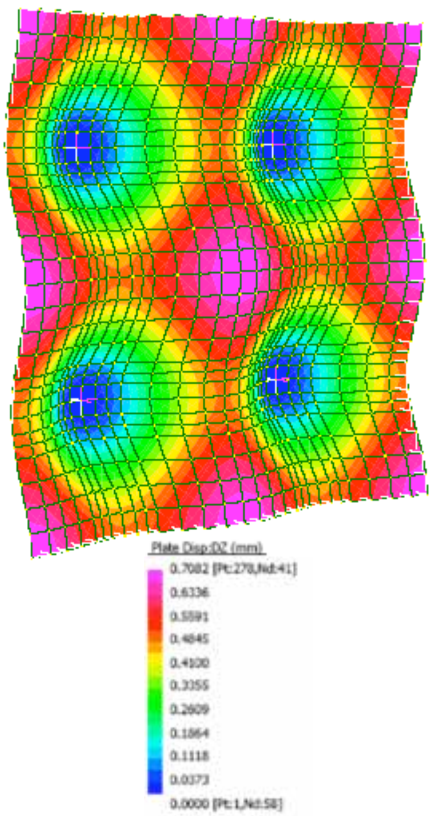


*Figure 7 Deflection contour diagram – debonding scenario 1T*

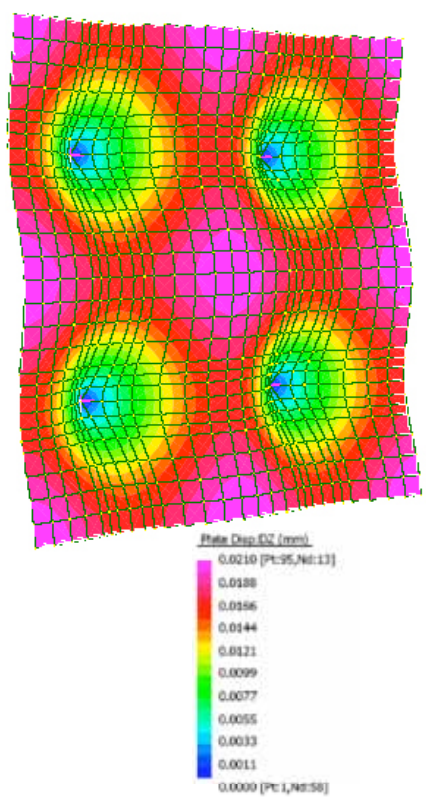


*Figure 8 Deflection contour diagram – debonding scenario 2*