LOW CARBON LIVING CRC

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CRC-LCL Impact Pathway 2 Summary Report: Delivering Low Carbon Materials, Products and Designs

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- originality
- methodology
- rigour
- compliance with ethical guidelines
- conclusions against results
- conformity with the principles of the Australian Code for the Responsible Conduct of Research (NHMRC 2007),

and provided constructive feedback which was considered and addressed by the author(s).

Executive Summary

Global warming is considered to be an issue of national and international significance and, if left unattended, a threat to future standards of living as well issues such as biodiversity and adaptability of the planet's sensitive eco-systems. Realising the severity of this issue, nations came together and agreed to act quickly to mitigate the worst of these effects through the *Paris Agreement* and set out clear and decisive targets for decarbonising so as to keep the global average temperature rise to well below 2 degrees Celsius above pre-industrial levels. Building and construction materials contribute one third of global greenhouse gas emissions (GHGE) and, despite having only 0.33% of the world's population, Australia has one of the highest per capita pollution and emission intensity levels.

Buildings produce a significant amount of carbon in their day-to-day use, with operational emissions from the built environment contributing an estimated 20% towards Australia's annual national total. Carbon mitigation strategies and standards developed by industry and government generally focus on these '*direct emissions*.' Another important part of the picture is the carbon emissions created during other stages of a building's life, such as in the production of materials and in construction. This *'embodied'* carbon contributes an additional 18% towards Australia's overall emissions, making it an important focus for new research and an enormous opportunity to boost built environment carbon reductions. Reduction in emissions can be achieved through appropriate material selection. As awareness of resource depletion and climate change grow, so too does the need for the construction industry to adopt more sustainable materials, technologies and practices. However, widespread uptake of alternative materials has yet to occur.

The Cooperative Research Centre for Low Carbon Living (CRCLCL) was launched in 2012 and aimed to provide government and industry with social, technological and policy tools to overcome identified market barriers preventing adoption of alternative products and services, while maintaining industry competitiveness and improving quality of life.

As part of the CRCLCL Program 1: Integrated Building Systems, Impact Pathway 2 aims to lowering the embedded carbon in buildings through developing low-carbon-lifecycle building construction components or materials. With these objectives CRCLCL undertook several projects to lower the embedded carbon in built environment. Its outputs target next generation construction practices, where step-change emission cuts are required and use of alternative carbon neutral materials needed. The Integrated Carbon Metrics (ICM) project aimed to build knowledge about both the direct and indirect carbon emissions in the building process and to better inform those making decisions about our future built environment. The ICM project developed carbon accounting tools that can scale to the building, precinct or city level, to provide a holistic picture of the carbon lifecycle in the Australian built environment. Carbon value engineering (VE) project verifies the current VE practices and has developed new method for carbon VE that account for entire life cycle of building materials. Other projects have successfully developed sustainable building materials from waste materials.

Portland cement is a major contributor to the total embodied emissions of building materials and thus recent research has been directed at improving the sustainability of cement-based products such as concrete and mortar. The use of supplementary cementitious materials such as fly ash and granulated ground blast furnace slag to improve properties and reduce the CO_2 impact of concrete is now well established. Further reductions in emissions are feasible with the use of alternative binders to Portland cement. One such binder is based on aluminosilicates and commonly termed '*Geopolymer*' or '*Alkali Activated Binders*'. One component of the CRC research was to identify pathways for enhancing the commercialisation opportunities of low CO_2 emission concrete and contribute to reduction of emissions in the built environment.

This report summarises the CRCLCL projects relevant to Impact Pathway 2- lowering embodied carbon, highlights the outcomes of each and draws relevant interconnections.

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1 Introduction

> "*If we don't take action the collapse of our civilisations and the extinction of much of the natural world is on the horizon,*" Naturalist David Attenborough reiterated in UN Climate Summit 2018 held at Poland. He added, "*Paris Agreement proved we can make real change*".

Described by Kevin Rudd in 2007 as "*the great moral challenges of our generation*", Global warming has high potential for extensive and extraneous impacts on society and is a challenge not only for the obvious environmental reasons but goes to economic and security issues as well. To mitigate global warming, the Paris Agreement (UN Climate Summit) sets out milestones and outlines action plans for each nation. Current projections show that the worldwide carbon emissions are increasing each year. The urgently required to turn towards a lower carbon emissions future has not been achieved yet, even less than the long-term goal of reducing the CO_2 concentration in the atmosphere. This trend, should it continue, is projected by scientific experts in climatology (IPCC, 2014) to lead to temperature raise greater than the generally accepted limit of a 2°C, if not reversed within the near future.

Buildings and construction materials account for nearly 40% of annual global energy use and around 30% of the global greenhouse gas emissions (GHGE), consumed and emitted throughout all stages in their life cycle (i.e. cradle-to grave) contributing significantly to the problem of climate change (IPCC, 2014; UNEP, 2009). The built environment – at all levels from materials to whole cities – is a key target sector for effective emission reductions. In recent years, 'zero carbon' building and city models have become increasingly popular, providing options for a future with a drastically reduced carbon demand. Zero-carbon living is the ultimate aim of a sustainable future that tackles the challenge of climate change. Materials, buildings and whole cities that do not add further GHGE to the atmosphere are at the heart of an environmentally sustainable built environment.

Despite having only 0.33% of the world's population, Australia has one of the highest per capita pollution and emission intensity levels (ABS, 2017; CSI, 2015). In 2013, the Australian construction industry was the third highest emitting sector, generating 90.3 Mt CO_2-e of indirect GHGE (from cradle-to-gate), generating 18.1% of the national carbon footprint, of which 47, 41, 10 and 2% were embodied in other heavy and civil engineering construction, residential and non-residential building construction, road and bridge construction, and construction services and imports, respectively (Tait, 2014; Yu et al., 2017).

To put this in context, Australia manufactures around 30 Mt of building products annually, which are predominantly concrete (56%), bricks (23%) and steel (6%) (Miller et al., 2015; Walker-Morison et al., 2007). A substantial amount of waste is also generated from the construction and building industry and landfilled, with 41% of total waste hailing from the construction and demolition stream (Hyder Consulting, 2011a, 2011b). Over the last half of a century, there has been a strong growth in the utilisation of construction materials in Australia and construction activity will continue to increase along with the nation's growing population.

To cope up with Paris carbon reduction agreement, Australia needs to reduce GHGE by 26-28%, below the 2005 level by 2030 (DEE, 2015). To meet this target, Cooperative Research Centre for Low Carbon Living (CRCLCL), an Australian Government initiative, undertook projects for low-carbon built environment in order to analyse the carbon fabric of Australia's built environment processes, quantify and track embodied emissions, evaluate low-carbon scenarios and define zero-carbon developments.

The CRCLCL has adopted eight Impact Pathways across three programs, representing specific areas in which CRCLCL expects to transform the low carbon-built environment. Impact Pathway 2 aims to lower the embedded carbon in buildings through developing low-carbon-lifecycle building construction components or materials. Its outputs target next generation construction practices, where step-change emission cuts are required. New design tools, rating frameworks and Australian Standards will underpin and stimulate the market for low carbon buildings, products and services. In view with this, the CRCLCL undertook several projects to lower the embedded carbon in the built environment. This report summarises the outputs of these projects, details the links between them and proposes future studies.

2 Background

The total life cycle emissions of buildings are the sum of operational and embodied emissions. The choice of building and construction materials can play a vital role in reducing embodied emissions, increasing the potential for recycling and the sustainability of the building. Mitigation strategies to reduce embodied emissions of building materials include replacement of emission intensive materials with low-carbon alternative materials, reduction of the use of carbon-intensive materials and the increase of the reuse and recycle of building materials (Giesekam et al., 2015; Pomponi and Moncaster, 2016; Sattary and Thorpe, 2016). Alternative materials include those that i) contain waste and recycled component, ii) incorporate reused content, iii) originate from natural matter, and iv) uses innovative production technology that has been optimised (Giesekam et al., 2015). Embodied impacts can only be reduced during the early phases of building design by the selection of low-carbon building materials.

González and García Navarro (2006) estimated that up to 30% reduction in carbon emissions is possible with the selection of alternative building materials. In a study by Huberman and Pearlmutter (2008), substitution of conventional building materials with alternative materials produced locally or using recycled content could save up to 20% of cumulative energy requirement over a life span of 50 years. Chen et al. (2001) presented that over 50% savings in embodied energy is possible if recycled aluminium and steel are used in residential buildings in Hong Kong.

The largest contributors within the total embodied emissions of building materials used in the Australian construction sector in 2013 are identified as cement, concrete, plasterboard, limestone, brick and other ceramics (39%), minerals (24%), iron and steel (10%), timber (9%), metals (9%) and plastic, polymer and rubber (6%) (Yu et al., 2017). Potential for emissions reductions by substituting the most commonly used building materials which have energy intensive supply chain (i.e. concrete) with a less energy intensive material such as geopolymer concrete (GPC) and timber will be explored in this research. Nevertheless, other factors such as facility performance and cost effectiveness should also be considered for the primary function of the building.

To address the above problems, CRCLCL initiated projects: (i) to quantify embodied emissions - Integrated Carbon Metrics (RP2007), ii) to reduce embodied carbon by Carbon Value Engineering (RP1034), iii) to develop sustainable low carbon product from waste material (RP1022) and, iv) to assess the performance of low carbon GPC (RP1004, RP1020).

The objectives of these projects are to improve methods and data for the analysis of embodied emissions in Australia that will be derived from an economy-wide modelling framework, to assess low-carbon scenarios and solutions for the built environment, to develop sustainable building materials and scientifically establish GPC as a sustainable alternative to Ordinary Portland Cement (OPC) concrete. The results of these studies have provided valuable information to the decision makers in the construction industry, as well as policy makers in designing strategies to meet carbon emission reduction targets.

3 Integrated Carbon Metrics (ICM) Project

3.1 Introduction

The main objective of this study was to harmonise different data and methods such as Life Cycle Assessment (LCA), Input Output Analysis (IOA) and Material Flow Analysis (MFA) to accurately calculate the embodied carbon emissions of construction materials in Australia. This study develops and streamlines efficient hybrid methodologies in analysing embodied emissions of the built environment at multiple scales and develops a comprehensive database of embodied carbon Life Cycle Inventory (LCI) data for building and construction materials that can be derived from an economy-wide modelling framework. The goals of this project were: i) to enable analysis of the carbon fabric of built environment processes, ii) to help assess the carbon performance of precincts, iii) to quantitatively evaluate low carbon scenarios, iv) to cooperate between researchers, industry, local and state authorities and v) to contribute to the process of defining universal carbon accounting principles, guidelines and standards. The project outcomes are summarised below.

3.2 Hybrid Life Cycle Assessment (hLCA) of GHGE from Cement, OPC and GPC

The development of low-carbon concrete is pursued to help the construction industry make its contribution in decarbonising the built environment. However, there is uncertainty around the actual amount of GHGE that can be avoided by employing alternative types of concrete. Existing studies evaluating environmental impacts of cement, concrete and GPC are predominantly based on process-based LCA with reference to standards ISO14040 and ISO14044. Process-based LCA has inherent methodological problem and in absence of country-specific data this method becomes less accurate and relevant.

In this study, Teh et al. (2017a), for the first time, employed input output (IO) based hybrid life cycle assessment (hLCA) to quantify the total embodied carbon emissions of cement and concretes produced in Australia accurately. The results of this hLCA study confirmed that GPC has the greatest potential to reduce GHGE compared to blended cement based and OPC concrete. Fly ash and ground granulated blast furnace slag (GGBFS) based GPC can substantially reduce GHGE by 32% and 43%, respectively, compared to standard OPC concrete with the same compressive strength using the economic allocation method. However, the adoption of GPC has been slow in Australia due to challenges such as the lack of long-term real-world data on durability, insufficient state and national level standard specifications, and industry hesitance to accept new materials (Marita et al., 2013). These issues are addressed by project RP1004 and RP1020.

3.3 Quantifying Embodied Emissions of Recycled Constructions Materials

Apart from low-carbon alternatives, waste minimisation strategies such as recycling construction and demolition waste are another way for the construction industry to contribute to a more sustainable development in the wider economy. However, only a comprehensive quantitative evaluation can assess whether the actual benefits of low carbon and recycled construction materials are realised if the whole life cycle of all processes is taken into account. Despite recent progress in hLCA methods, some weaknesses remain with respect to the inherent uncertainty relating to price variations and aggregated sectors that are unable to provide detailed waste-specific information.

In this study, Teh et al. (2018) proposed a mixed-unit hybrid LCA (MU-hLCA) approach based on a combination of process LCI, IO, and material flow data that are used to model the economy-wide potential use of recycled construction materials in Australia. A comparison between methods of life cycle emissions of GPC revealed that the MU-hLCA approach produced a more accurate and Australian-specific result. The usefulness of the proposed mixed-unit IO model is demonstrated through quantifying the cradle-to gate embodied emissions of recycled construction materials and by-products utilised in concrete and steel sectors in Australia. The results yield a 1% reduction when recycled concrete aggregate completely replaces natural aggregate in both OPC concrete and GPC. GHGE reduction of 30% is quantified for GPC using recycled concrete aggregate compared with OPC concrete utilising natural aggregate. The method merges physical and monetary units of industrial systems related to low-carbon alternatives and recycled construction materials to enable the calculations of embodied carbon with improved accuracy.

3.4 Decomposition of Integrated Hybrid Life Cycle Inventories by Origin and Final-Stage Inputs

Teh and Wiedmann (2018) develop a method to decompose LCI derived from MU-hLCA and integrated hLCA. The approach extended the decomposition method described by Wiedmann (2017) that distinguished embodied impacts originating from industries and products in a SUT framework. For hLCA methods such as the integrated hLCA and MU-hLCA, the input-output table (IOT) is augmented to include an additional LCI process matrix (Suh, 2004; Suh and Huppes, 2000), but none of them have shown the explicit contribution of processes to the total hybrid LCIs.

The decomposition of integrated hybrid LCIs by final-stage inputs method is able to show life cycle emissions originating from industries, products and processes. It is especially useful when the C^d matrix is used to model specific processes that are aggregated in the IOT (Suh 2006). In conclusion, this method is useful for enriching carbon footprint results by way of a new angle and interpretation, namely to answer the questions “how much life cycle impact is derived from final-stage inputs” (using the “by final-stage inputs” method) and “where do emissions ultimately come from” (using the “by origin” method).

3.5 Replacement Scenarios for Construction Materials

As part of the ICM project, this study evaluates construction material replacement scenarios at the economy-wide scale. Teh et al. (2017b) investigated the potential use of Engineered Wood Products (EWPs) in new building stock to assess the carbon outcomes of a potentially significant shift in the use of construction materials. The selection of low-carbon and sustainable building materials is crucial in reducing the built environment’s carbon footprint. The main objective of the replacement scenario analysis was to assess the potential reduction in future GHGE by replacing the use of reinforced concrete with EWPs.

Amended National Construction Code (NCC) and the Building Code of Australia (BCA) have allowed for the construction of residential and non-residential buildings up to 25 meters in height (or approximately 8 stories tall) in accordance with Deemed-to-Satisfy provisions, which include the use of both EWPs like Cross Laminated Timber (CLT) and traditional lightweight timber framing. Although NCC and BCA allow timber buildings of up to a maximum of 8-stories, the scenario analysis references the 10-story apartment Forte as a model building because it is a real-life example of an existing building in Melbourne. Outcomes of this study will help further understand the implications of substituting alternative building materials that are more sustainable and which can be utilized as main structural products in the construction industry in Australia.

By comparing residential and non-residential building stock scenarios using an IO-based hLCA method, this study was able to gain some insight into potential emissions reductions opportunities. If 100% of new residential building structures were to be constructed from EWPs instead of 100% reinforced concrete, a saving of 26 Mt CO_2e can be achieved by 2050. This saving is even greater when sequestration is considered, with a potential to reduce emissions by 119 Mt CO_2e. Similarly, if 100% of new commercial building structures were to be constructed from EWPs instead of 100% reinforced concrete, a saving of 13 Mt CO_2e can be achieved by 2050 and when sequestration is considered, a higher emission saving of 28 Mt CO_2e can be achieved.

Australia should aim to achieve net zero operational emissions buildings by the year 2050 if it were to comply with the Paris Climate Change Agreement commitments. This study shows that this alone would not be sufficient as the building sector continues play a crucial role in carbon emissions through embodied emissions. Hence, the use of timber as a low embodied energy construction material is to be recommended in the construction of buildings, at least with respect to lowering GHGE.

3.6 Building of Data Base

Aside from methodology, data is also an important determinant of the quality of a quantitative or LCA study (Schaubroeck and Gibon, 2017). As part of the ICM project, an Australian-specific hybrid database of embodied carbon LCI for major building and construction materials that was produced in this study using IOA, IO-based hLCA and MU-hLCA has been made available. The full list of building materials' hybrid data is provided in Teh (2018). This will be useful to architects, consultants, planners and the public for a more accurate assessment of the carbon impacts of their projects, products or buildings. Embodied carbon data will also act as inputs to the tools developed by the ICM project, which are used to analyse and minimise embodied carbon emissions incurred in the life cycle of materials, buildings and precincts.

3.7 Embodied Carbon Explorer (ECE) Tool

National Carbon Offset Standard (NCOS) for Precincts provides new guidelines for carbon neutral precincts (Commonwealth of Australia, 2017) which can be done by i) preparing a carbon account (for scope 1-3), ii) reducing emissions where possible, iii) offsetting emissions that cannot be reduced or avoided, iv) preparing a public report on carbon neutrality, and v) arranging for an audit of the carbon account and public report. However, there are currently no tools in the market directly targeting assessments under the NCOS Precincts.

Accounting for the multitude of contributions from supply chains is usually a complicated and a time intensive task using the bottom-up approach. Alternatively, a top-down approach can quantify scope 3 emissions easily and rapidly by using Australia-specific IO data, making it a more efficient technique. Based on the top-down approach, ICM project has developed the ECE online tool based on the Australian Industrial Ecology Virtual Laboratory (IELab) to enable the rapid evaluation of (scope 3) carbon emissions in a wide range of products and services (e.g. precinct, building, organisation, etc.). It is well suited for a quick screening assessment before full, detailed assessments are undertaken. The ECE tool can quantifies the total scope 3 carbon emissions related to a project, identifies main contributors to the total scope 3 carbon emissions and provides NCOS -suitable functionality. The ECE tool supports the realisation of the NCOS standard and has the theoretical potential to realise carbon neutrality for all new precinct developments and refurbishments. ECE tool can be found at: https://ece.ielab-aus.info/.

3.8 Precinct Carbon Assessment (PCA) Tool

ICM project has developed PCA tool that examine the whole life cycle of carbon emissions (scope 1, 2 and 3) on the precinct scale and to calculate different low carbon scenarios, including travel modes and renewable energy systems, for precincts and precinct development projects. The PCA i) can assess predicted and operational carbon performance, ii) offers three levels of precinct carbon modelling, i.e. the building level, the product level and the material level, iii) quantitatively evaluates low carbon scenarios to inform ‘Business as Usual’ type of development, supports planners, designers, and government agencies for more effective planning and mitigation and iv) is flexible to operate across states, urban settings, and the development project life cycle.

The PCA tool is not bound by data sources. It allows users to adjust precinct morphological settings, building types, travelling modes, renewable system options, and carbon intensity data of precinct objects for conducting quantitative analysis and finding the optimal solutions. The tool can be applied to Greenfield or Greyfield-type development for Residential, Commercial or Mixed-use precincts. The spatial scales in modelling and assessments include Street, Neighbourhood, Subdivision and Suburb, as well as CBD.

The PCA tool supports the realisation of the NCOS standard for precincts (http://www.environment.gov.au/climate-change/government/carbon-neutral/ncos) and has the theoretical potential to realise carbon neutrality for all new precinct developments and refurbishments.

4 Carbon Value Engineering

4.1 Introduction

This project (RP1034) sought to maximise the reduction of embodied carbon in the built environment. In this connection two studies were conducted: i) to explore the carbon impact of current industry-standard practice of Value Engineering (VE) in Australia and ii) to develop a holistic Carbon Value Engineering methodology to integrate life cycle cost and whole life carbon emissions at the initial stage of decision making process (Robati et al. 2018).

4.2 Impact of VE on Building Initial Embodied Carbon and Cost

Value engineering is a process where cost reduction and constructability are optimised prior to building construction. It is a mandatory practice for all NSW government projects with a value exceeding AUD $5million. In addition to the cost, an increase in environmental awareness has also highlighted the need to include potential environmental benefits into the VE process. The trade-off between cost and environmental impacts is critical in the decision-making process. The aim of this study was to examine the relationship between environmental impacts and building costs associated with current VE practices.

To achieve this objective, a complex mixed-use building in Sydney was modelled to determine the capital material costs and initial embodied carbon emissions before and after the VE process. This study considered the CO_2-e emissions associated with the extraction of raw materials, manufacturing and processing. This is often known as ‘cradle-to-gate’. VE process was applied to 188 building items.

The study analysed the impact of building components on the overall embodied CO_2-e emissions and capital cost. Prior to VE, the building had an initial embodied carbon of 44,601 tCO_2-e, or 528 $kgCO_2$-e/m². Its material cost was $55.4million, or $655.95/m². After VE, the initial embodied carbon was 44,038 tCO_2-e, or 521 $kgCO_2$-e/m² and costs were $55.0 million and $651.26/m². This equates to a 1.26% saving of embodied carbon and a 0.72% saving of material costs.

This trend indicates the potential positive impact of conventional VE strategies on the embodied carbon emissions and added value to the building. The saving of 6.67kgCO2-e/m² may seem small, but when multiplied across the Australian built environment, its impact can be significant. According to COAG (2012) 2,814,000m² of new non-residential floor area is predicted to be constructed in 2019. If this was subject to a 6.67 $kgCO_2$-e/m² saving, the result would be a reduction in 18,769 tonnes of CO_2-e/year.

4.3 Carbon VE Methodology to Integrate Life Cycle Cost and Whole Life Carbon Emissions at the Initial Stage of Decision-Making Process

Despite an increase in environmental awareness, there is a lack of methodology on how to integrate environmental and economic performance at this early stage. This study proposed a holistic Carbon VE methodology to integrate life cycle cost and whole life carbon emissions at the initial stage of decision-making process. This Carbon VE framework is a quantitative value analysis method, which not only estimates cost but also considers minimal impact on the natural environment for alternative design solutions.

The case study building on which VE process was undertaken has been adapted in this study. The building was redesigned to explore alternative design and structural strategies that optimise the building for reduced cost and life-cycle carbon emissions simultaneously. The base building was designed as reinforced concrete (RC) structure with flat plate floor to validate the practically of the structure. Other design strategies such as RC structure with flat slab floor or post-tensioned floor, steel structure with steel deck floor or CLT slab and timber structure with CLT elements were considered. The lifetime carbon emissions and life cycle cost were determined for each alternative design options.

The building was assessed for 50 years lifespan. This study finds that the type of structural systems can have considerable effects on both cost and carbon emissions of the building. For example: the use of timber as main structural material could save up 13% or 98 $kgCO_2$-e/m^2 in lifetime embodied carbon emissions of the building, and its lifecycle cost was reduced by 5% or \$66/m^2 (equivalent to \$2,853,114 saving in cost). This study also examined the implication of using GPC in overall carbon emissions and cost of buildings. The GPC can save up to 16% or 119 $kgCO_2$-e/m^2 in embodied carbon emissions and 5% or \$66/m^2 in life cycle cost of mass timber building.

4.4 Project Outcome

The results from this study confirm the potential impact of VE practices on the carbon emissions of the case study building. It also highlights the need for considering both VE and embodied carbon analysis at the same time in the process of evaluating design alternatives.

This study has developed a holistic framework to evaluate lifetime economic and environmental performance of alternative solutions at the initial stage of decision-making. The developed framework was used to determine the potential impacts of non-conventional approaches to dematerialisation in building design. The obtained results of this study revealed a significant saving in the carbon emissions and cost can be achieved through appropriate selection of building materials and structural systems.

This study also shows that Mass timber and Post-tensioned building are the most economical and ecological friendly than the other design solutions for a case study building. It was found that the building designed out of Timber (Mass timber) could potentially reduce embodied carbon emissions by 36% or 267 $kgCO_2$-e/m^2 and life cycle cost minimised by 10% or \$127/m^2. A comparison study revealed that the embodied carbon saving could be equivalent to 8 years cumulative operational carbon emissions in a most environmental and cost-friendly alternative.

Connection of RP1034 with Other Projects

This project integrated the LCA database developed by ICM project (RP2007). ICM project's database provides comprehensive information on carbon emissions associated with various construction materials used in Australia (Teh 2018).

This study employed Australian building material emissions factors which have been developed by the CRCLCL (Wiedmann, 2017). Costs associated with building materials are taken from the Australian construction handbook based on 2017 data (Rawlinsons, 2017).

This study suggests that use of GPC can reduce 16% carbon emissions than that of base design. This outcome justifies the studies undertaken in RP1004 and RP1020 on GPC.

5 Sustainable Low Carbon Products from Waste Materials for Built Environments

5.1 Introduction

Project RP1022 explored the potentials for manufacturing sustainable building materials from waste materials. Accelerating consumption and short replacement cycles are driving significant increases in waste volumes worldwide; over the past decade the average volume of waste generated in the world's urban areas has doubled and projections for the next decade suggest a further 70% rise (What a Waste, a global review of solid waste management, 2012). Recycling technology trying to recover the waste resources fails to keep pace with the rapid consumption, causing a steady increase in waste volumes (EPA, 2017).

Waste glass is one of the fastest-growing solid waste streams worldwide. In Europe, approximately 1.5 million tonnes of waste glasses are landfilled annually due to building demolition and renovation (Hestin et al., 2016). Similarly, in Australia, the waste glass also rises to nearly 800,000 tonnes per year (FEVE, 2017). Waste glass is a growing burden and new options are urgently needed for the large volumes of mixed, broken and contaminated glass that cannot currently be recycled.

To increase glass recycling rates, alternative means of reprocessing mixed waste glass in a single waste stream is therefore required. Use of this waste glass as construction raw materials might be among the most attractive options because of the volume of raw materials involved, and the likelihood to use the fabricated products in bulk. The primary objective of this project was to demonstrate the potential feasibility of utilizing end-of-life mixed waste glass as valuable raw materials for secondary products. A summary of the newly developed composites and the waste raw materials is given in Table 5.1 and a brief description of each study are discussed in subsequent sections.

Table 5.1. Newly developed composites and their raw materials from waste

Studies	Produced composites	Raw materials from waste
Study-1	Polymeric glass composite (PGC)	Waste glass powder
Study-2	Polymeric glass aggregate composite (PGAC)	Waste glass powder, coloured glass and colour powder
Study-3	Powder-resin-composite	Quartz off cut, sand, seashells, dolomite, concrete waste, limestone aggregate and limestone dust
Study-4	$CaSi_3$ as wollastonite and pseudo-wollastonite	Glass powder and seashells
Study-5	Wood-plastic composite (WPC)	Waste wood powder from saw dust, polypropylene from disposable plastic food container and waste glass powder
Study-6	Cup-resin-composite (CRC)	Paper plastic laminates (PPL) from paper cup and glass powder

5.2 Polymeric Glass Composite (PGC)

This study developed cost-effective new processes that transform large quantity of mixed waste glass into PGC. Waste glass from diverse stream e.g. window glass, tempered glass, laminated glass and borosilicate glass were mixed with epoxy casting resin and silane coupling to process this new composite. Details of this study can be found in Heriyanto et al. (2018a).

This study demonstrated that a high quality and versatile product, comparable to engineered stone, could be produced primarily from waste glass powder. Fig. 5.1 shows compressive and flexural strength of PGC are well comparable to engineered stone. The PGC panels are designed to serve as high-quality benchtops for kitchens and bathroom vanities and as wall and floor tiles. Given the emerging global challenged posed by waste and the need for low-cost, locally available inputs for manufacturing, this process offers an important alternative for the waste glass that cannot be remelted in conventional recycling processes.

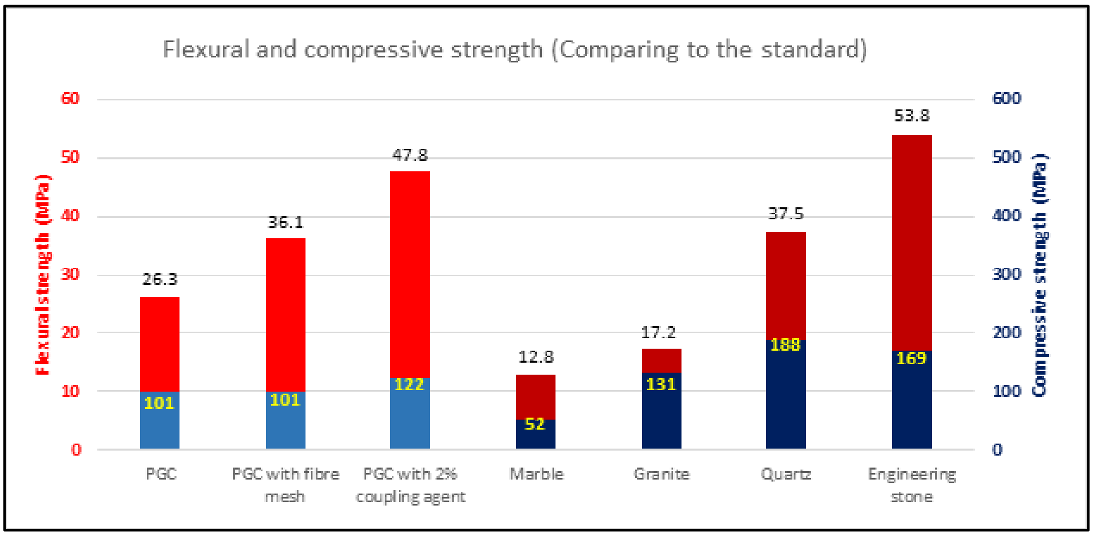


Fig. 5.1. Comparison of mechanical properties of PGCs with the natural and engineering stone.

5.3 Polymeric Glass Aggregate Composite (PGAC)

This study developed a novel formulation of polymeric glass aggregate composite (PGAC) from PGC with addition of coloured glass aggregates. The system used replicated gap-graded composite system in concrete where the intermediate sizes of aggregate are missing. As PGAC contains 85% of waste material and without the need of high temperature, the study embodies another economic and environmentally friendly pathway for glass recycling. Waste coloured glasses and colour powder were added to PGC. Details of this study can be found in Heriyanto et al. (2019a).

Mechanical tests were conducted for flexural, compression, water absorption, and scratch resistance test. PGAC exhibits Mohs hardness of 5.5 – 6.0, highly water resistance, and moderate resistance to fire and high temperature. The production process of PGAC does not require high temperature as like ceramic tiles that has made it very cost effective. PGAC's mechanical and physical properties were proved to stand above that of natural stones. The application of this glass panel is designed to serve as kitchen countertops, bathroom vanities, tiles for wall and floor.

5.4 Powder-Resin – Composite

This study developed an innovative pathway for successfully synthesizing composite panels using various waste input. For this purpose, seven types of powder from waste or widely available filler i.e. Quartz offcut, sand, waste seashell, dolomite, limestone aggregates, concrete waste and limestone dust were used. This study assessed the effectiveness and mechanical properties of these waste powders in the production of powder-resin composites. Details of this study can be found in Heriyanto et al. (2019b).

Marine-based epoxy, namely Clear Cast and amino-based coupling agent were mixed with the waste powder at optimal resin/filler ratio. Under high compaction pressure and heat densified powder-resin composite panels were produced with high mechanical properties. Compression strength, scratch resistance, and water absorption were also reported in this study.

The composite panels in this study are designed to replicate the natural look of marble, granite, travertine, terrazzo and solid colour panels. These new approaches of using powder filler in resin-based composites can be a new alternative to produce green materials that provide both environmental and economic benefits.

5.5 CaSiO3 Compounds – Wollastonite and pseudo-Wollastonite

Shell waste imposes a major financial and operational burden on the shellfish processing and food industries. Although there are many potential uses for waste shells, there is no optimum solution to treat or use these by-products (Fitzgerald, 2007). This study developed a new pathway for successfully synthesising calcium silicate compounds using 100% waste inputs at a processing temperature significantly lower than conventional approaches. Using a solid-state reaction of two common wastes - powdered float glass from building demolition and seashells discarded by the food industry, wollastonite and pseudo-wollastonite were obtained. Details of this study can be found in Heriyanto et al. (2018b).

Mechanical properties such as the hardness, flexural and compressive strength of the calcium silicate compounds produced were investigated in this study. It can be seen from Fig. 5.2 that the flexural strength increased in line with increasing processing temperature, with the highest average value of 30.1 MPa achieved at 1200^0 C. Compressive strength was also improved significantly with increasing temperature. The mechanical properties of the slab also compared favourably to ceramic tiles. It is expected that the results and concept of this study can be used as a promising new way to create cost-effective, high quality calcium silicate compound slabs, as a potentially cheaper, sustainable alternative to high temperature ceramic tiles.

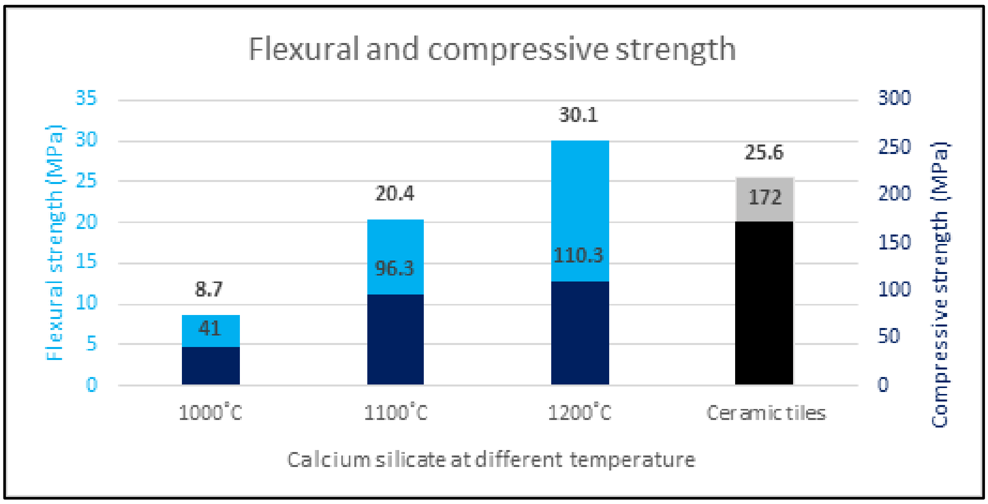


Fig. 5.2. Flexural and compressive strength of calcium silicate compound at different temperature

5.6 Waste Glass Powder (WPC)

WPC have emerged as an essential family of engineered materials worldwide (Caulfield et al., 2005; Pilarski and Matuana, 2005). WPCs are used globally in building applications, such as decking, docks, landscaping timber, fencing etc. and in furniture, automotive and other consumer products (Bowyer et al., 2010). This study developed a novel and cost-effective means of enhancing the porosity, stiffness and resistance to moisture/water, swelling and fire of WPC. This solution opens a new opportunity for transferring 100% wastes into resources. Details of this study can be found in Heriyanto et al. (2018c).

The raw materials in this study were sourced from waste as wood powder from saw dust, polypropylene from disposable plastic food container and glass powder from mixture of different waste glass product. Mechanical properties, specially water absorption and fire retarding capacity of WPC are reported. The results suggest that the mechanical and physical properties of WPC can be enhanced significantly by tailoring particle size, coupling agent, and glass content. The addition of glass powder from 5 to 30% by weight transformed the WPC in to stiffer, less porous and better resistance to moisture/water absorption, thickness swelling, and fire.

5.7 Cup-Resin-Composite (CRC)

Disposable cups used for serving coffee and tea are made from high-quality virgin cellulose fibre board called paper plastic laminates (PPL) glued with a solvent-based adhesive. This study demonstrated the utilization of wastepaper cup and glass in manufacturing high-performance composite materials. PPL, glass powder, resin binder and amino silane coupling agent were combined to produce the composite. The goal of this study was to establish commercial uses of a substantial amount of waste cups and glass in the manufacture of secondary products.

The mechanical performances as well as water permeability and thickness swelling of the novel panel were measured to be comparable to the standard high-density fibreboard board. The results and concepts of the findings are expected to be used as a promising means to produce high-performance composites, as a potentially sustainable and cost-effective alternative for recycling paper cup and glass waste.

5.8 Prototyping, Testing and Demonstrating the Industrial Scale Production of Composite Engineered Stone

RP1022 project has successfully developed waste material based six composites for sustainable build environment. By leveraging the expertise and process for developing of a new generation of high-performance engineered stone for building, furniture and architectural applications, RP1022u1 aims for processing and production of glass composite panel at an industrial scale.

In this project, processing parameters from lab-scale to industrial-scale production will be fine-tuned. The design, properties and production trial will be investigated with end users to support commercialisation. In the long term, the project represents a significant advance in reducing the carbon generation during production of building materials as it overcomes the costly need for extraction of raw materials, transportation and production of already exist product in the market.

The success on this project will provide a cost-effective, technical viable new solution that supports the goal of producing low carbon and sustainable products with high performance at compatible price. The current status of this project is:

-SMaRT centre, UNSW conducted waste audit in collaboration with Wollongong University in local council Wallgett for better understanding the real situation of waste in local councils.

-Hot press machine has been procured and installed at Terrazzo Australian Marble in Arndell Park.

6 Geopolymer Concrete

6.1 Introduction

Construction of the built environment involves use of natural resources and creation of GHGE. Production of OPC alone is responsible in generating approximately 5-7% of CO_2 emissions worldwide (Chen et al, 2010). The average CO_2 emissions associated with the manufacture of cement are 0.93 and 0.82 tonne/tonne of cement in US (Marceau, 2006) and Australia (Flower and Sanjayan, 2007), respectively. One component of the CRC research is to identify pathways for commercialisation of low CO_2 emission concrete and contribute to reduction of emissions in the built environment. The increasing potential threats to environment imposed by CO_2 have promoted the development of inorganic polymer binder called 'geopolymer' which involves the reaction between solid aluminosilicate materials with alkaline solutions. Sources of aluminosilicates include fly ash, blast furnace slag and metakaolin. Alkali-activated slag and alkali-activated fly ash are synonymous terms to geopolymer in this context. GPC offers potential benefits in reducing the greenhouse gas emissions associated with conventional concrete based on OPC.

ICM (RP2007) and CVE (RP1034) projects noted that GPC can contribute in the reduction of embodied carbon significantly. However, conventional concrete is a long-established material entrenched in the construction industry and the use of alternatives such as GPC faces many barriers.

Marita et al. (2013) conducted a detail study to identify the barriers to widespread adoption of GPC. An industry survey was also performed to better understand barriers particular to GPC in Australia and to identify potential pathways to overcoming these barriers. Highest priority activities were identified as: (i) development of a handbook through Standards Australia specific to GPC that include performance requirements and provision for use of in state and local specifications and (ii) independent research on GPC engineering properties, durability and field performance. The handbook would be the outcome of the research conducted in the field of GPC. In view with that several studies were undertaken and are summarised below.

6.2 Mechanical and Materials Properties

Noushini et al. (2016) and Noushini and Castel (2016) conducted detail studies on class F fly ash-based GPC cured at various conditions. The aim of this studies was to develop a comprehensive experimental data set on mechanical and transport properties of GPC and propose a constitutive model to represent the complete stress-strain curves for ambient and heat-cured low-calcium fly ash-based GPC. Three different curing regimes were applied to the GPC and the OPC concrete specimens: lime-water curing, sealed ambient curing and heat curing. Twelve different heat curing conditions applied to the identical concrete samples consists of three different temperatures of 60, 75 and 90 ^{0}C and four curing periods of 8, 12, 18 and 24 hours. Brief conclusions from the studies are outlined below.

Compressive Strength

GPC develop compressive strengths depending on the heat curing regime. The strength increases with the increase in the curing temperature up to 75 ^{0}C and curing duration up to 24 hours. Heat cured GPC can achieve more than 90% of the 28 days strength after 1 day. For example: in this study GPC cured at 75 ^{0}C for 24 hours achieved 60.2 and 62.3 MPa at age 1 day and 28 days, respectively. Ambient cured fly ash-based GPCs attained a very low compressive strength at early ages, for example, 2.9 and 40 MPa at age 1 day and 28 days, respectively. Therefore, for precast applications, low-calcium fly ash-based GPC appears to perform better than OPC in term of both early and long-term compressive strength and porosity, using the same amount of binder.

Modulus of Elasticity

GPC generally tends to have lower modulus of elasticity compared with OPC, particularly if fly-ash based. Depending on the heat curing regime, modulus of elasticity of GPC for 40 MPa concrete varied between 13.5 and 25.9 GPa at 28 days. The existing stress-strain models developed for OPC concrete, such as Collins and Mitchell's (1991) model predicts a lower stiffness and a lower strain at peak stress for heat-cured GPC. This study proposed a new compressive stress-strain model for heat-cured low-calcium fly ash-based GPCs that can accurately model the stress-strain behaviour.

Ultrasonic Pulse Velocity

The pulse velocity of GPCs ranges between 3210 and 3930 m/s while this range is 3720–4350 m/s for OPC concrete samples. Like OPC, the pulse velocity in GPC samples is increasing with increase in the compressive strength and modulus of elasticity.

Water Absorption

Heat-cured and ambient-cured GPC exhibited a lower absorption value (5.4–6.0%) compared to their counterpart OPC concrete (6.3–7.1%). Only limewater cured OPC concrete demonstrated lower water absorption of 5.0% compared to the GPCs.

Volume of Permeable Voids (VPV)

Inappropriate curing condition such as curing temperatures lower than 75 ^{0}C and curing durations lower than 18 hours would increase the VPV in geopolymer concrete. The VPV of the properly heat cured fly ash-based geopolymer is very similar to that of its counterpart OPC concrete cured in standard limewater bath.

Sorptivity

Sorptivity represents the material's ability to absorb and transmit water through the matrix by capillary suction. GPC heat-cured at 60 ^{0}C showed higher sorptivity compared to the ambient cured samples. Heat-curing of fly ash-based GPCs at 75 and 90 ^{0}C for 18-24 hours results in a lower sorptivity than the ambient curing thereby indicating lower porosity or less interconnected capillary pores.

Surface and Bulk Resistivity

For saturated GPC, the resistivity increases with an increase of the curing temperature and time. A strong and linear correlation between compressive strength and resistivity has been observed for GPC. The highest value of resistivity for the geopolymer specimen is recorded at the compressive strength of around 60 MPa. The GPC resistivity decreases by 50% when strength decreases from 60 MPa to 40 MPa. This result shows that similar to the conventional OPC concrete, compressive strength can be a reasonable measure of the overall quality of GPC.

6.3 Time Dependent Behaviour of GPC

Castel et al. (2014) and Castel et al. (2016a) conducted study on the time dependent behaviour of GPC. Both drying shrinkage and creep tests were performed according to Australian Standard AS 1012.13 and AS 1012.16, respectively. Different curing regimes at elevated temperature were used. All experimental results were compared to Australian Standard AS 3600 predictions.

Shrinkage

It has been found that the type and temperature of curing strongly influences the magnitude of shrinkage. The age at which shrinkage testing begins is also influential. It was observed that:

- Specimens cured at low temperature such as 40 ^{0}C for 1 day, shrinkage strains at 56 days were about three times than that of calculated using Australian Standards AS 3600. Similar specimens cured for 3 days at 40 ^{0}C temperature attained Australian Standards AS 3600 requirements.

- Specimens cured at 80 ^{0}C temperature for 1 day, shrinkage strains meet the Australian Standards AS 3600 requirements.

- The simplified (empirical) models developed for AS 3600 models hold no relevance for alkali-based GPC and are not appropriate for use in such applications. Thus, drying shrinkage be measured on GPC in accordance with AS 1012.13 over a period of 90 day. It is also important to use test curing conditions representative of those under which geopolymer concrete will be produced.

Creep

Castel et al.'s (2016a) study showed that heat-cured fly ash-based GPC undergoes low creep. In this study, the creep coefficient was about the third of the one calculated using Australian Standards AS 3600 for the specimens cured three days at 40 ^{0}C. After 7 days at 80 ^{0}C, creep strains tend to a value close to zero.

Castel et al. (2016b) performed another study on five reinforced GPC beams to assess the time-dependent deflection and crack widening of GPC beams under long term sustained loading. The time-dependent performance of GPC beams in term of serviceability appears to be better than that of OPC concrete beams due to the very low creep coefficient of heat cured GPC. The time-dependent increase in GPC beams deflection is very low and greatly smaller than that observed on OPC beams. All results show that the crack widths of GPC beams are significantly smaller than those expected for OPC concrete beams according to *fib* model code 2010 for both short and long terms tests. It is concluded that low calcium fly ash-based GPC is a promising option for precast applications.

6.4 Bond Strength

Castel and Foster (2015) studied the GPC bond with both deformed and smooth, round, reinforcing steel bars using the standard RILEM pull-out test method. This standard test method allows plotting the bond stress–slip diagram for GPC. Results are compared to the performance of a reference OPC-based concrete. The geopolymer binder was composed of both low calcium fly ash and GGBFS. Considering that GPC is well suited for precast applications, tests aim to investigate the development of the bond strength from 24 hours to 28 days after casting using different heat curing conditions.

The results of this study show that:

- The mechanical characteristics and bond strength of GPC depend on the curing condition. After 48 hours of heat curing at 80 °C, performances of the GPC were found to be similar to that of the OPC reference mix.
- For an equivalent compressive strength, the GPC bond strength was observed to be slightly better than that of the OPC reference concrete; a 10% increase in the bond strength was observed, on average.
- The overall bond stress–slip curves observed for both types of concrete are very similar. Thus, existing models allowing predicting the bond behaviour of traditional concretes can be used for GPC with similar compressive strength and will provide conservative results.
- Tests performed using smooth bars showed that the chemical adhesion of GPC to the steel surface is similar to the one observed on the reference concrete. Providing an intensive heat curing, the development of the early age bond strength of geopolymer specimens is better than the one observed on traditional concrete specimens cured at ambient laboratory temperature (23 °C). The bond strength of the GPC after 2 days of heat curing was superior to the one of the reference concrete after 28 days. Those results show that Class F fly ash GPC is particularly well suited for precast applications.

6.5 Durability

Australian Standard AS 3600-2018 gives the specification for the design of concrete for durability. The specification is largely performance-based in that the required functional properties of the concrete are specified. Given that GPC do not have the same lengthy track record as OPC, there are some uncertainties regarding long-term behaviour.

Corrosion of reinforcement is the most common and obvious form of durability failure. This can manifest itself as anyone, or a combination of, surface staining, cracking along reinforcement close to a surface and spalling of a surface. The process of corrosion is divided into two phases—initiation and propagation. Steel reinforcement is protected against corrosion by the high alkalinity of the GPC surrounding it (Babaee and Castel 2016). In the initiation phase, the protection afforded by the alkalinity of the concrete can be reduced by three processes—carbonation (neutralization of the high pH by infiltration of atmospheric carbon dioxide), ionization (an increase in the concentration of reactive ions such as chlorides), and alkali leaching. In the propagation stage, the reinforcement will corrode at a rate that depends on the availability of oxygen and moisture, the temperature of the concrete, the presence of reactive ions and residual alkalinity.

Carbonation

Carbonation, as one of the main durability threats, plays a detrimental role to concrete by reducing the alkalinity of the pore solution at the vicinity of reinforcing steel. This may lead to the depassivation of reinforcement, leaving them prone to corrosion. For the OPC concrete, the hydration product portlandite ($Ca(OH)_2$) provides a buffer effect in which the continuous dissolution of portlandite maintains the high pH level of the pore solution in case of neutralization of the OH^- ions during the carbonation process. Unlike the OPC binders, low-calcium fly ash based geopolymer-type binders do not contain a considerable amount of portlandite as a reaction product; and as a result, they might be more prone to the loss of alkalinity. There is relatively little existing knowledge on the carbonation process in low-calcium FA GPC.

The performance of GPC against carbonation is very variable depending on the mix design with only little correlation with concrete compressive strength. Carbonation coefficient is typically higher than that of OPC concrete with similar strength. As a result, a performance-based specification is needed for GPC members when atmospheric carbonation is a concern. Khan et al. (2017) has conducted study on carbonation of GPC. It was observed that existing equation given by Ho and Lewis (1987) for carbonation in OPC can be used for GPC for both accelerated and natural conditions. Khan et al. (2017) showed that accelerated test should be carried out using a CO_2 concentration of 1% as 1% CO_2 concentration develops the same reaction products as in normal atmospheric condition (i.e. 0.03% CO_2).

Babee et al. (2018) observed that low level of alkali concentrations in the pore solution ([Na]~0.2 mol/l) can provide enough protection for the reinforcement during natural carbonation. On the other hand, very low alkali concentration in the pore solution ([Na]<0.2 mol/l) will increase the risk of depassivation considerably. Dissolution of sodium bicarbonates/carbonates can lead to a re-alkalinisation of the carbonated pore solution; this is important for structures where there is the coupled effect of carbonation and high relative humidity/moisture transportation.

Alkali-Silica Reaction

Theoretically the risk of an alkali–silica reaction (ASR) appears to be higher in GPC compared with OPC concrete due to the high alkali content of the activator. Published works on ASR in GPC revealed that the degree of reaction vastly depends on the mix design. Mahanama et al. (2019) conducted study on the GGBFS content on the ASR in geopolymer mortar. They successfully used accelerated mortar bar test (AMBT) to assess the effect of geopolymer binder calcium content in ASR. It was observed that geopolymer mortar with 10% GGBFS in binder is proven to be ASR resistive. Expansion using highly reactive aggregate stabilized was close to 0.1% (lowest expansion specified in AS 1141.60.1) even after 150 days. Providing the very harsh conditions in AMBT (1 M NaOH at 80°C), it can be safely assumed that the risk of ASR in geopolymer mortar with GGBFS content less than 10% is very low. Geopolymer mortar with 20% and 50% of GGBFS content in binder exceeded the 0.1% limit eventually, but final expansion was less than that of OPC mortar bars.

Chloride Induced Corrosion

Regarding the initiation phase of chloride induced reinforcement corrosion process, performance of GPC concrete against chloride diffusion is highly variable and depends on the mix design with only little correlation with concrete compressive strength. As a result, specification for concrete structures in marine environment is required to be performance-based.

Babaee and Castel (2016) studied the chloride-induced corrosion of reinforcement in low-calcium fly ash-based GPC. In their study reinforced low calcium fly ash-based GPC samples exhibit polarization resistance values comparable to Portland cement-based corroding systems. This behaviour can be interpreted as a similar electrochemical performance of both binders when used in chloride-contaminated environments. Overall corrosion rate of reinforcement in GPC is very similar to that usually observed in traditional concrete.

Noushini and Castel (2018) recommended three testing methods to assess the capability of GPC to resist against chloride penetration: ASTM C1556, NT BUILD 492 and ASTM C1202 test methods. The testing protocols are the same as those for traditional OPC but the performance-based requirements have been recalibrated for GPC.

6.6 Performance Evaluation of Geopolymer against in situ Aggressive Sewer Environment at Sydney Water

Concrete is one of the most widely used construction materials in wastewater collection, transportation and treatment plant. In wastewater, concrete is susceptible to multistage deterioration under highly acidic environment. The deterioration of concrete especially, in sewer pipes as a result of microorganism which produces sulphuric acid is termed as “Microbially Induced Concrete Corrosion” (MICC). This study was aimed to evaluate the performance of geopolymer mortar in aggressive sewerage environment.

Five different mortar specimens were prepared, namely low calcium fly ash based geopolymer mortar (FA-GPm), slag based geopolymer mortar (Slag-GPm), calcium aluminate cement (CAC), special purpose sulphate resistant cement mortar (SRPCm) and Geospray mortar by Miliken Infrustructure Solutions. To study the corrosion of mortar specimens as a result of biogenic activity, they specimens were placed in an actual sewer environment at North Head wastewater treatment plant, Manly, Sydney. Testing has been performed on the specimens up to two years in natural conditions in three different digesters with varying aggressiveness.

After six months scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) mapping of FA-GPm showed denser microstructure as compared to CAC, MM and SRPCm with very limited sulphur penetration. After 2 years of exposure in natural infield conditions the following observations were made:

FA-GPm performed better compared to SRPCm in all three natural sewer environments in term of visible deterioration, loss of mass and compressive strength reduction. The estimation of surface pH indicating the loss of alkalinity was much greater in case of SRPCm, however, stage II of MICC estimated from this assessment showed that it has commenced in FA-GPm before SRPCm. Moreover, by comparing the neutralization of specimen, it was estimated that greater neutralization was observed in FA-GPm compared to SRPCm. Microstructural assessment showed deterioration of FA-GPm due to dealumination and loss in alkali however, the crystallization of gypsum was not extensive due to low concentration of calcium in geopolymer mortar. In contrast, widespread crystallization of gypsum was observed within the matrix of SRPCm after dissociation of C-S-H gel causing increase in porosity and loss in structural integrity.

6.7 Field Trial of Geopolymer Concrete

Development of High-Density GPC for Breakwater Armour Units for Port Kembla Harbour

Breakwaters are designed to ensure the protection of ports, harbours and coastal beaches by breaking waves and in dissipating wave energy. Hostile marine environment and episodic storms continually damage these breakwaters posing threat to the coastal structures. Concrete armour units are widely used in breakwaters. As the armour unit stability is a cubic function of submerged relative density, a small increase in the material density may result in a significant enhancement of armour stability and, therefore, a significant reduction in total armour unit weight and volume.

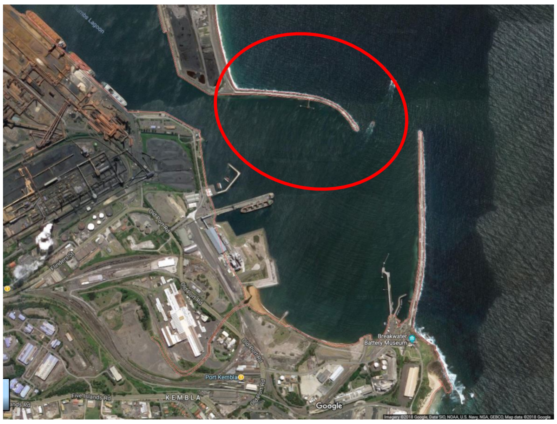
Aggregate occupies three-quarters of the concrete by volume. The use of high-density aggregate is a convenient way to produce high-density concrete. Steel furnace slag (SFS), a by-product of steel manufacturing industries, has 25-30% higher density than conventional basalt aggregate (Brand and Roesler, 2015; Khan et al., 2016; Wang and Yan, 2010). A substitution of conventional aggregate with SFS can provide a high-density end product.

In this project a high-density SFS aggregate based GPC has been developed for use in armour (Hanbar) units designed for coastal protection. This unique high-density GPC addresses two major issues of our time – climate change and the sustainable use of resources. These concrete uses blended fly ash and slag as the binder, and steel furnace slag as aggregates; all of which are by-products of respective industries. Use of no cement in the concrete combined with less material is an effort to a reduced carbon footprint associated with cement production.

After extensive research work a high-density GPC mix-design was developed at the UNSW laboratory. Then Wagners (Toowoomba, Queensland) was engaged to refine the laboratory mix to field delivery at scale; some minor adjustments were made to adapt the mix design to their commercial methods. The field-design mix was batched using Cleary Brothers commercial plant, located at Port Kembla and with that 13 high-density GPC 17.4-tonne Hanbar units were cast (Fig. 6.1)

The results of the laboratory tests and subsequent microstructural analyses confirm that SFS aggregate GPC can be a promising material in manufacturing high-density armour units for breakwaters.

The density of the concrete is found to be acceptably higher than conventional concrete and has the potential to significantly reduce armour unit size without compromising the structural stability of breakwaters, with a size reduction as much as 50%. Thirteen high density GPC Hanbar units have been placed on the north breakwater at NSW Ports' Port Kembla Harbour. In terms of next steps, these units are being monitored for stability and integrity and will provide a valuable benchmark for future use of GPC. This could allow for the upgrade of existing breakwaters with reduced cement requirements, placement cost, and overall footprint, to provide increased stability while retaining good interlocking with existing armours. Details can be found in Mahmood et al. (2018).



(a)

(b)

Fig. 6.1. High-density GPC (a) site location- Port Kembla northern breakwater (Google maps) (b) GPC Hanbar Armour Unit.

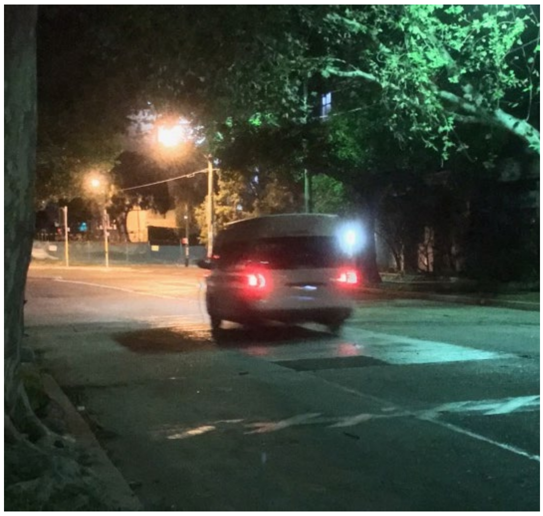
GPC Pavement at Alexandria with City of Sydney

From several studies it has been now agreed upon that GPC has many superior qualities, including higher tensile strength, durability and improved resistance to chemical deterioration in the marine environment. However there have been many challenges in making GPC behave like traditional concrete in terms of such things as ease of pumping, setting time and curing requirements. Making GPC is further complicated by the need to ensure that there is no contamination between concrete types, so batching the concrete in standard concrete facilities is difficult. This project was undertaken with the concrete industry to produce perfect GPC and make it useable in construction.

(a)

(b)

(c)



(d)

Fig. 6.2. GPC pavement at Wyndham Street, Alexandria, Sydney (a) reinforcement, (b) vibration strain gauges, (c) GPC pavement just after casting and (d) the first traffic driving over GPC pavement at 5 am after 36 hours of casting.

With the collaboration of City of Sydney, a GPC trial pavement (15 x 3m) has been constructed at the Wyndham Street, Alexandria, Sydney (Fig. 6.2). To compare GPC pavement's performance, an OPC concrete pavement has also been casted next to it as such that both pavements experience similar real time traffic. The GPC mixed was produced by Wagner. Cylinders and prisms were collected from site for testing of mechanical property, shrinkage and creep. To monitor the pavement's long-term performances under real traffic, resistance strain gauges and vibration strain gauges were placed inside the pavements prior to concrete pouring and are being continuously monitored. The pavements were cured under ambient condition. In situ testing by Schmidt hammer showed that GPC attained approximately 15- 20 MPa compressive strength in 24 hours and no surface cracking was developed. Due to strict requirement from Roads and Maritime Services, NSW the road needed to open to traffic just after 36 hours of casting. The concrete samples were cured in standard 23 ^{0}C temperature with controlled humidity at UNSW laboratory. The 28 days compressive strength and indirect tensile strength were found to be 41 MPa and 3.9 MPa, respectively. The both GPC and OPC concrete pavements are being monitored.

6.8 Handbook for GPC

Previous study and industry survey (Marita et al, 2013) clearly identified the lack of inclusion of GPC in existing Australian standards (e.g., AS 3600) and state or local specifications and lack of industry guidelines or recommended practices, lack of standard specifications, and lack of education and training as significant barriers in implementing GPC. It was recommended to develop a Handbook through Standards Australia titled “Guide and Standard Specification for Construction with Geopolymer and Alkaline Activated Binder Concrete”. This handbook will be an authoritative document to provide engineers and end-users with practical information and specification clauses necessary for integrating GPC into construction projects. Project RP2020 has accumulated extensive data on the properties of GPC and based on those a handbook has been prepared. The handbook includes relevant performance-based specifications and test methods to meet service requirements.

At the time of writing this report, a sub-committee on Standards Australia BD2/9 has been established to prepare the handbook and to make recommendations to the committee of the Concrete Structures Standard AS 3600 (Standards Australia Committee BD002) for consideration in the 2021 edition of the Standard. It is expected that the Handbook will be published towards the end of 2019.

7 Future Studies

7.1 Introduction

As awareness of resource depletion and climate change grow, so too does the need for the construction industry to adopt more sustainable materials, technologies and practices. However, widespread uptake of alternative materials has yet to occur. In the time since the establishment of the CRC for Low Carbon Living in 2012 considerable progress has been made in proving of new low carbon construction materials and in establishing them as commercially reliable alternatives to traditional materials – much of this acceleration can be directly attributed to the work of the CRC and in doing so, providing government and industry with the technological and policy tools needed to overcome identified market barriers to preventing adoption of alternative products and services. While, as stated, the work of the CRC has gone someway to breaking down commercial barriers and identifying and filling crucial research gaps, further work is needed. This short section identifies just a few of the arears where further research is needed to continue the efforts in lowering Australia's carbon emissions from the construction sector.

7.2 Low-carbon construction materials

The ICM project investigated several low-carbon construction materials including GPCs, Electric Arc Furnace steel, EWPs and recycled aggregates. Other emerging natural, renewable and recyclable building materials should be evaluated as an extension of this research in order to have a wider coverage of sustainable options for the built environment and to achieve set emission targets. Few recommended materials for future research are: (i) hemp-based materials for building applications (e.g. insulation mats, concretes and bio-composites) due to their carbon sequestering and low GHGE attributes compared to glass fibres, (ii) stabilised mud blocks can provide energy savings of around 60% to 70% compared to burnt clay bricks (Venkatarama Reddy, 2009) and (iii) rammed earth construction techniques offer a variety of advantages, including low-carbon emissions, low energy intensity and the materials utilised are recyclable (Venkatarama Reddy and Prasanna Kumar, 2010).

7.3 Global multiregional input-output data

With growing international trade, it is also important to model the impacts of imports and exports of products. The effects of international trade could also be modelled with MU-hLCA, by combining national IO data and global multi-regional input-outputs (GMRIO) data. GMRIO can be a key element of hybrid methodologies that are applied in product-related environmental impact assessments, including sustainability standard adherence, 'eco-friendly' certifications and carbon footprint analysis (Wiedmann et al., 2011). Depending on the source of GMRIO database selected a more detailed level of sectors can be provided. GMRIO could be hybridised by including specific process data (e.g. transport) to enumerate the emissions from international transport. Wiedmann et al. (2011) discussed the cautionary allocation of bunker fuels and related emissions from international transport for further research in this area.

7.4 Sustainable building products from waste materials

This study has established the use of waste mixed glass as raw materials to produce different composite panels for building environment. Despite their possible uses, the produced panels are lab scale products (240 x 240 x 20 mm). Possible future research direction is to upscale the size to industrial scale and increase the production rate is therefore needed. This work has started.

The possible uses of other types of waste plastic, i.e. Styrofoam, waste acrylic to replace resin are one way to produce the next generation glass-polymer composite from 100% waste. This study has successfully produced a Styrofoam-glass powder panels that has similar look to that of glass powder resin composite. However, investigation on the mechanical properties, its limitation as well as additive required are still in progress and require further studies

7.5 Alkaline Activated Binder and Geopolymer Concrete

Considerable work was undertaken by CRC-LCL in identifying the research gaps in bringing Alkaline Activated Binder and GPC to the market in a large way. Much of this evolved around establishing durability and service behaviour and in developing robust models for these. Some significant trails were established; most notably the Geopolymer pavement slab at Wyndham Street with the City of Sydney Council, and several structures are currently being monitored for their performance (Foster et al., 2018).

There remain a few significant areas where research is needed to fill vital gaps in the knowledge of Geopolymer and Alkaline Activated Binder Concrete for its full application. The most significant of these are behaviour in shear and torsion, in scaling of creep and shrinkage models developed at the materials level (small scale under a limited set of controlled environmental and loading conditions) to structural sized applications, including the effects of size, environment and loading.

Further work is needed in broadening the number, variety and scale of demonstration projects. There is a great need for large public government businesses enterprises, such as roads and bridge authorities, to step up and lead the way for change and adaptation, as was historically the case, but, sadly, is not now.

8 Conclusions

The CRC for Low Carbon Living's research builds on multidisciplinary expertise, existing technology development, social research and national benchmark software tools. While international research suggests some possible pathways for carbon reduction in the built environment, the CRCLCL is particularly necessary for discovering the underlying principles of low carbon living in the Australian context, addressing the unique requirements of the Australian climate, construction practices, demographics and policy environment. To help Australia in achieving carbon emission reduction target set in Paris Agreement, CRCLCL has adopted eight Impact Pathways across three programs to transform the low carbon-built environment. Impact Pathway 2 aims to lowering the embedded carbon in buildings through developing low-carbon-life cycle building construction processes and materials. Several projects were undertaken in this regard and summarised in this report. The briefs outcomes are as follows:

Total embodied carbon emissions, for the first time, have been quantified for (i) cement and concrete produced in Australia using hybrid life cycle assessment method and (ii) recycled construction materials employing a proposed mixed-unit hybrid LCA method. This study confirms that GPC can substantially reduce GHGE by 32% compared to standard OPC concrete and when recycled concrete aggregate replaces natural aggregate in both OPC concrete and GPC, 1% carbon reduction can be achieved.

Construction material replacement scenarios at the economy-wide scale have been evaluated by investigating the potential use of EWPs in new building stock. Study found that if 100% of new residential and commercial building structures were to be constructed from EWPs instead of 100% reinforced concrete, a saving of 147 Mt CO_2e can be achieved by 2050, when sequestration is considered. This study recommends the use of timber as a low embodied energy construction material with respect to lowering GHGE.

An Australian-specific hybrid database of embodied carbon LCI for major building and construction materials has been developed. This will be useful to architects, consultants, planners and the public for a more accurate assessment of the carbon impacts of their projects, products or buildings.

Online tool- Embodied Carbon Explorer (ECE) based on the Australian Industrial Ecology Virtual Laboratory has been developed to enable the rapid evaluation of (scope 3) carbon emissions in a wide range of products and services (e.g. precinct, building, organisation, etc.). It is well suited for a quick screening assessment before full, detailed assessments are undertaken.

This project has developed The Precinct Carbon Assessment (PCA) tool that examine the whole life cycle of carbon emissions (scope 1, 2 and 3) on the precinct scale and to calculate different low carbon scenarios, including travel modes and renewable energy systems, for precincts and precinct development projects.

The study on value engineering confirms the potential impact of value engineering practices on the carbon emissions of a building. A holistic framework has been developed to evaluate lifetime economic and environmental performance of alternative solutions at the initial stage of decision-making. A comparison study revealed that the embodied carbon saving through this process could be equivalent to 8 years cumulative operational carbon emissions in a most environmental and cost-friendly alternative.

Project RP1022 explored the potential of manufacturing sustainable building materials form waste materials such as waste glass. This study has developed six types of engineered composite panels using 100% waste materials. Work is underway to transform these products at industrial scale.

Extensive research has been done on GPC to determine its (i) mechanical, and transport properties, (ii) shrinkage and creep, (ii) durability - carbonation, chloride-induced corrosion, ASR, (iv) performance in aggressive sewerage environment. Based on the experimental data a Handbook on GPC has been prepared.

To test the performance of GPC on site two field trials have been done: (i) development of breakwater armour with high-density GPC for Port Kembla Harbour and (ii) GPC concrete road pavement at Wyndham Street, Alexandria, Sydney. The performances of both projects are being monitored.

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