Final Project Report

FTP2- Recycled Waste in Concrete for Municipal Applications

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Acknowledgements and Project Team

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Project Team members and their roles in the project.

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Staff-A	Prof. Filippo Giustozzi	RMIT University	Academic	Research support
Staff-IS	Julie Atkinson / Matt Loughlin	OPV	Project Lead	Connect the project team to local councils for coordination of trials.
Staff-IS	Johnathan Kapelles	Hanson	Project Lead	Development of concrete pre-mix delivery
Staff-IS	Daniel Kabel	Mornington Peninsula Shire Council	Project Lead	Advise on footpath trial and location
PDRA	Dr. Yanlin Wang	The University of Queensland	Post-Doc Fellow	Researcher
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Category

Staff=Academic and Industry Staff
PDRA=Post-doctoral Fellows
Student=Honours, PhD or Master Student

Personal Type for A

Project Leader
Research Assistant
Engineer
Senior Engineer
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Administration
Primary Supervisor
Associate Supervisor
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PhD

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Executive Summary / Abstract

This project centred on developing and evaluating concrete mixes that incorporate industrial by-products and recycled materials as partial substitutes for cement and aggregates in municipal applications. It aims to assess the performance of waste-based concretes in meeting the mechanical and durability standards required for municipal infrastructure, positioning them as a sustainable alternative to traditional concrete and helping reduce environmental impact. Additionally, the project serves as a strategic response to the demand-supply imbalance in the Victorian infrastructure and waste recovery sectors, with a primary focus on local councils and municipalities.

The research in this project is divided into two main phases: laboratory investigations and field trials. The laboratory phase includes the mix design, preparation, and testing of concrete incorporating polyethylene terephthalate (PET) fines, high-density polyethylene (HDPE) flakes, crumb rubber (CR), and ground-granulated blast-furnace slag (GGBFS). Six waste-based concrete mixes were developed, and their mechanical performance and durability were assessed under controlled laboratory conditions. The experimental results showed that five of these mixes met the performance standards required for footpath construction.

Following the laboratory investigation results and an assessment of the overall environmental impact and cost, two developed concrete mixes were selected and adapted in collaboration with the supplier, Hanson. These mixes were used to place two footpaths at Mornington Peninsula Shire, Victoria. Visual inspections and feedback from contractors indicated that the concrete demonstrated good workability and achieved the required strength and durability under field conditions, confirming its suitability for municipal infrastructure applications.

The findings of this project indicate that waste-based concrete can offer a low-carbon alternative to traditional concrete in footpath construction. By repurposing PET and CR, these materials help reduce landfill waste, conserve natural aggregates, and decrease the carbon footprint of concrete. As a result, this project provides a viable pathway for the construction industry and municipalities to integrate low-carbon, resource-efficient materials into infrastructure projects. Additionally, the continuous recycling capability of the developed concrete was examined, highlighting the potential to enhance the sustainability of construction practices.

The next steps involve scaling up the use of these mixes in different environments and climatic conditions to evaluate their consistent performance. Further research is needed to assess the long-term durability of these mixes under various environmental conditions and material degradation. Additionally, it is recommended to investigate potential environmental risks, such as soil contamination, conduct detailed microstructural analyses of pore characteristics in the concrete, and develop predictive models for shrinkage and creep.

This project lays the groundwork for advancing waste-based concretes, setting a benchmark for sustainable practices in municipal construction. By demonstrating the shift from laboratory research to real-world applications, it underscores the potential of waste-derived materials to support green infrastructure and contribute to the circular economy goals within the concrete industry.

1. Industry Problem, Needs and Relevance

1. What are the specific problems or challenges your research is intended to address?

This project is a strategic response to the growing demand-supply imbalance in infrastructure development and waste recovery in Victoria. As population growth and infrastructure expansion continue to increase the demand for concrete, which heavily relies on natural aggregates, the supply of these resources is diminishing. Projections suggest a shortfall of over 4 million tonnes of quarry materials by 2050 [1]. Meanwhile, substantial volumes of waste generated by municipal, commercial, and construction activities are ending up in landfills, wasting materials that could otherwise be repurposed. There is a clear need for innovative solutions to transform waste materials into viable concrete alternatives, reducing landfill waste and alleviating pressure on limited natural resources.

In addition to the depletion of natural resources and the burden of landfill waste, the construction sector is a major contributor to greenhouse gas (GHG) emissions. Australia's commitment to the Paris Agreement sets a GHG emissions budget of 4,353 million tonnes of CO_2 equivalent (Mt CO_2-e) from 2021 to 2030 [2]. Since committing to this GHG budget, 1,276 Mt CO_2-e has been emitted, leaving 3,077 Mt CO_2-e remaining. The construction sector alone has contributed 23.15 Mt CO_2-e, roughly 2.66% of the country's total emissions [3]. Given that the lifecycle of civil structures involves multiple sectors such as mining, manufacturing, transport, and waste management, it's reported that around 70% of Australia's emissions are linked to infrastructure projects [4]. The emissions from traditional concrete production, particularly from cement, emphasise the urgent need for alternative materials that can mitigate the environmental impact of construction.

Therefore, there is an immediate need to explore opportunities that connect the surplus of recycled materials in the waste recovery sector, the growing demand for materials in urban and infrastructure development, and the need to reduce GHG emissions in construction. Addressing this imbalance will support the construction industry in a more sustainable direction. This project serves as a timely platform for collaboration between government, industry, the supply chain, asset owners, and academia to advance the development of sustainable infrastructure.

2. Why are these problems not being solved today? e.g. high cost, complexity, lack of knowledge, etc. What are some specific blockers and problem types preventing the industry from overcoming these challenges?

Despite the growing demand for construction materials, the use of recycled products in the industry faces economic challenges that limit their adoption. Natural aggregates are often more affordable due to government subsidies, large-scale production, and well-established supply networks, making them a more cost-effective choice for builders. In contrast, recycled materials tend to be more expensive due to the additional processing required. For example, natural river sand typically costs between $45 and $90 per tonne, while crumb rubber (CR), a recycled alternative, can range from $500 to over $800 per tonne [5]. Due to the significant difference in specific gravity between CR and river sand, a volumetric cost comparison provides a practical basis for material selection in concrete mix design. Based on typical specific gravities, this equates to approximately $119–$239 per m^3 for river sand and $540 to over $864 per m^3 for CR. This significant price disparity discourages the use of recycled materials in construction. Furthermore, maintaining a consistent, high-quality supply of recycled materials is difficult due to the variability in the sources and types of available waste materials.

Technical and regulatory barriers also hinder the widespread adoption of recycled materials in construction. Although extensive research has been conducted on concrete containing recycled materials, most studies focus on short-term mechanical properties with limited insights into long-term durability. Practical applications remain limited, as much of the research is confined to laboratory conditions, mainly addressing material performance rather than evaluating performance in structural components or infrastructure. To confirm their viability in real-world construction applications, comprehensive durability testing and large-scale field trials are essential.

Additionally, limited awareness and knowledge transfer among contractors, asset owners, and regulatory bodies further prevent the widespread use of recycled materials. Most existing standards and specifications for concrete are based on natural aggregates, providing little guidance for incorporating alternative materials. While some technical reports and guidelines on the use of recycled materials have been developed by Austroads [6,7] and VicRoads [8], these resources fall short of offering detailed, practical instructions for their application. The lack of clear guidance, coupled with limited understanding of the benefits and performance of recycled materials, creates substantial barriers to their adoption. Therefore, developing a comprehensive technical guideline for the use of recycled materials in construction is crucial.

3. Who specifically faces these challenges and problems today? Capture the cost to the industry in $ where relevant. Is it preventing productivity? Or preventing non-monetary benefits like sustainability and environmental goals? Or preventing better decision-making?

The challenges outlined above impact various stakeholders within the construction and waste recovery sectors. Asset owners, builders, and infrastructure developers are particularly affected by the higher cost of recycled materials compared to natural aggregates. However, as traditional concrete production, which relies on cement and natural aggregates, is a significant contributor to Australian GHG emissions, it is possible that conventional concrete will eventually require carbon credits to offset these emissions. The current average price for an Australian Carbon Credit Unit (ACCU) is approximately \$36.42 per tCO_2-e [9]. For conventional 32 MPa concrete, emissions are around 0.108 tCO_2-e higher per cubic meter compared to concrete that uses supplementary cementitious materials (SCMs) [10]. This difference could lead to an additional carbon offset cost of about \$3.93 per cubic meter, a figure likely to rise as the cost of carbon credits increases.

Moreover, contractors face substantial challenges when working with concrete incorporating recycled materials, mainly due to the lack of established performance standards. This absence of standardised specifications creates uncertainty about factors like application scope, concrete placing, and curing. Additionally, the inherent differences between recycled and natural aggregates make it difficult for suppliers of recycled materials to consistently meet the required specifications for concrete production. These challenges hinder the broader adoption of recycled materials and impede progress toward circular economy, sustainability, and GHG emission reduction goals.

2. Project Objectives, Hypotheses and Impact Pathways

1. What specific industry challenges does this project address?

This project addresses several key industry challenges related to the adoption of recycled waste materials in concrete construction. First, it reduces the reliance on virgin, finite quarry-based materials by substituting them with sustainable household, commercial, and industrial waste products. Second, it diverts waste materials, which would traditionally end up in landfills, into valuable commodities. Third, it enhances the confidence of key stakeholders—such as the supply chain, asset owners, and government—in both short- and long-term decision-making by addressing environmental concerns and ensuring asset performance.

2. What key hypotheses are investigated in this project? What underlying assumptions were investigated? How did you define what success looks like in investigating these hypotheses?

The primary hypothesis of this project is that concrete incorporating recycled waste materials can meet the mechanical and durability requirements for municipal footpath applications. It is assumed that up to one-fifth of the total natural aggregate by weight in the mix can be replaced, and that an appropriately designed concrete mix using plastic waste, rubber, and GGBFS could result in a 20% reduction in GHG emissions, with GGBFS accounting for around 90% of this overall reduction.

Success is primarily defined by the development of concrete mixes that meet the footpath requirements outlined in Australian standards. Further evaluation will focus on reductions in GHG emissions, measured in accordance with ISO standards, along with the conservation of natural aggregates and minimisation of landfill waste. The target is to achieve a 20% reduction in both GHG emissions and natural aggregate by weight.

3. What impacts does this project aim to enable? Impacts should include value to the economy or environment, value that can be unlocked by overcoming the identified industry problems, value propositions for end users, business case benefits for an industry partner, etc. Be specific and measurable. Are there key governmental or institutional strategic priorities that this project aligns to?

The primary impact of this project lies in its significant environmental benefits. By incorporating recycled waste materials, the developed concrete mixes help reduce landfill demand and conserve natural aggregates. Additionally, they contribute to lowering GHG emissions, supporting both national and global climate action goals. Compared to conventional ordinary Portland cement (OPC) concrete, as outlined in the Green Star concrete guide [11], the developed concrete mixes achieve the following reductions per cubic meter at the same strength: a 5.35% to 30.56% decrease in GHG emissions, a 33.57% to 48.33% reduction in cement by weight/volume, a 29.48% to 38.07% reduction in fine natural aggregates by weight (27.37%-46.63% by volume), and save 0.056 m^3 to 0.114 m^3 of landfill space. Field trials and contractor feedback confirm the workability of the developed concrete, indicating its strong potential as a ready-mix concrete for footpath applications. This project aligns with the National Reconstruction Fund Corporation (Priority Areas) Declaration 2023 [12], focusing on renewables and low-emission technologies.

4. Impact Pathways: How will the concrete industry implement the outputs or otherwise adopt the research outcomes? What is the role of project participants at this time? What are the longer term go to market plans, from small-scale to large scale?

The concrete industry can directly adopt the developed mixes, as their properties have been experimentally and practically validated at various scales, including laboratories at the University of Queensland, RMIT University, and Hanson, as well as through field trials. Local premixed concrete supplier Hanson and contractor DM Roads consulted on the mixes to ensure they met practical requirements. The recycled materials used in the mixes were sourced from local suppliers Tyrecycle and Visy.

Project partners are crucial in promoting the adoption of these materials by incorporating them into future projects. Over time, these developed concrete mixes could be expanded to other non-structural components and infrastructure, based on the success of the field trials. Partners can also help ensure a consistent supply of recycled materials. Large-scale implementation will rely on a steady supply of recycled materials and the establishment of detailed technical standards for incorporating recycled materials into concrete of varying grades.

The long-term go-to-market plan follows a phased approach, starting with small-scale applications and progressing to larger-scale projects. The initial focus will be on footpath projects, collaborating with various councils in different environmental conditions, with ongoing visual inspections. This phase will allow the mixes to be tested for performance, durability, and cost-effectiveness in real-world conditions. These projects will validate the mixes, provide valuable construction experience, and build confidence in their practical application.

The next phase will involve scaling up to larger projects, such as external building paths, ground slabs, and external car parks, where the mixes can be used in larger volumes of non-structural concrete. During this stage, ensuring a consistent supply of recycled materials will be critical, as will refining technical standards to accommodate various concrete grades. Additionally, the long-term durability, especially the skid resistance, permeability and porosity, of the mixes in field conditions, including potential contamination issues, will be investigated to confirm their overall performance. The proposed key activities for these phases are outlined below:

Activities	Description and purpose	Timeline
Footpath trials	• Assessing the performance of the developed concrete. • Evaluating the benefits and limitations of using the developed mixes in practical construction under different environmental conditions.	2023-2025
Market analysis	• Exploring supply chain dynamics, focusing on consistent recycled materials. • Assessing the demand for low-grade or non-structural concrete.	2023-2025
Environmental, safety, and health investigation	• Assessing the long-term concrete degradation and potential environmental issues, such as soil contamination and microplastic concern. • Identifying potential health risks.	2024-2026

Development of practical construction guidelines	• Developing a detailed technical guide covering supply, delivery, placement, curing, and maintenance processes.	2025
Large-scale applications	• Assessing the feasibility of the developed concrete in large volumes.	2025-2026
Refinement of guidelines	• Defining material requirements, performance expectations, and practical construction and maintenance for different applications. • Updating technical guidelines based on insights from large-scale applications.	2026
Market strategy and plan	• Identifying target application areas, customer profiles, and competitors. • Developing marketing tactics and sales strategies.	2026
Legal matters and risk management	• Finalising regulatory compliance and training manuals. • Establishing risk assessment and management protocols.	2026

3. Project Methodology and Key Activities

The testing activities included mechanical and durability tests, along with environmental impact assessments conducted using life cycle assessment (LCA). To evaluate whether the hypotheses or assumptions were proven or disproven, the mechanical and durability performance of the developed concrete mixes was compared to the requirements outlined in AS 3727 [13] and VicRoads 703 [14]. The results demonstrated that the tested material met these requirements, thereby supporting the hypothesis regarding its suitability for footpath applications.

The environmental impact of the developed concrete was assessed using ISO-based LCA methodologies and compared with the reference concrete specified in the Green Star concrete guideline [11] at the same strength. This comparison highlighted the environmental benefits, offering valuable insights to validate or refine assumptions concerning sustainability.

The specific tests, standards, and facilities used are listed in the table below:

Property	Test	Equipment/Tool/Solution	Standard
Particle size distribution	Sieve analysis	• Sieve • Shaking machine	AS 1141.11.1
Slump	Slump of freshly mixed concrete	• Slump mould • Rod • Scoop • Baseplate • Ruler	AS 1012.3.1
Mass per unit volume	Mass per unit volume of freshly mixed concrete (fresh density)	• Measuring bowl • Balance • Rod • Mallet • Scoop • Glass cover	AS 1012.5
Air content	Air content of freshly mixed concrete	• Air chamber system (measuring bowl, air meter, cover assembly) • Rod • Mallet • Scoop	ASTM C231/C231M
Compressive strength	Compressive strength of	• Grinding machine	AS 1012.9

	concrete@7, 28, 90 and 365 days	• Universal testing machine	
Elastic modulus	Static modulus of elasticity of concrete@28, 90 and 365 days	• Grinding machine • Universal testing machine • Compressometer	AS 1012.17
Tensile strength	Splitting tensile test and flexural tensile test@28, 90 and 365 days	• Grinding machine • Universal testing machine • Bearing strips • Testing jig • Vernier calliper • Ruler • Supporting rollers • Loading rollers	AS 1012.10 AS 1012.11
Chloride Penetration Resistance	Four-point Wenner array probe test and rapid Chloride permeability test@28, 90 and 365 days	• Surface resistivity apparatus • Vacuum pump • Applied voltage cell • Specimen-cell sealant • Sodium Chloride solution • Sodium Hydroxide solution • Constant voltage power supply • Shunt resistor • Voltmeter	AASHTO T358 ASTM 1202
Uniformity and relative quality	Ultrasonic pulse velocity test@28, 90 and 365 days	• Pulse generator • Transducers (transmitter • and receiver) • Amplifier • Time measuring circuit • Cable	ASTM C597

Apparent volume of permeable voids	Water absorption test@28, 90 and 365 days	• Balance • Water tank • Water bath • Oven	AS 1012.21
Abrasion resistance	Abrasion test@28, 90, 365 days	• Rotating cutter • Drill press • Weight plate	ASTM C944
Carbonation resistance	Accelerated carbonation test@ 28, 90, 365 days	• Carbonation chamber	ISO 1920-12
Drying shrinkage	One-year drying shrinkage test	• Environmental chamber • Length comparator • Reference bar	AS 1012.13
Creep	One-year creep test	• Grinding machine • Environmental chamber • Loading frame • Strain gauge	AS 1012.16

a) What prior work did this work build upon? Include research, papers, projects and intellectual property that this project leveraged. Was there any background IP that the university contributed? Was there background IP that you required from industry partners?

This project is built on the insights [1, 13] gained from a previous grant project that was a collaboration between Sustainability Victoria, the Office of Projects Victoria (OPV), RMIT University, Boral, and the City of Whitehorse. The focus of that project was to investigate, develop, and test mix designs that incorporated Victorian household plastics and rubber as a replacement for aggregates. The research leveraged new knowledge and methodologies developed throughout the project. The outcomes of that project have been published for wide access.

b) How was this research unique/novel? Was there competing research, solutions or technologies that solved the same industry problems, and how was this solution better than other market leaders? Who were these competing individuals, research organisations and/or businesses?

The research conducted in this project was unique in (1) optimised concrete mix design incorporating multiple recycled materials from diverse waste streams, (2) the comprehensive long-term property investigation of concrete incorporating recycled materials, and (3) LCA and field trials of the developed mix design to provide dual validation in terms of performance and sustainability.

There have been many competing studies undertaken. However, most remain at the laboratory scale or preliminary assessment stage. The current competing studies have three key limitations: (1) insufficient testing, with a lack of comprehensive long-term experimental evaluations; (2) a narrow focus on recycled materials, often using only one or two types as cement or aggregate replacements; and (3) limited practical applications, as many developed concrete mixes are not implemented in real-world engineering scenarios or subjected to LCA for environmental impact assessment. Furthermore, the mix designs employed in some LCA studies are doubtful as they contain very low cement content, which, although potentially achieving target strength, may require extended curing times, making them unsuitable for projects with tight schedules.

This project stands out from competing research due to (1) comprehensive long-term durability tests, providing greater confidence in long-term performance, (2) optimisation of mix designs by balancing the benefits and limitations of recycled materials to maximise waste reduction while meeting strength requirements, and (3) conducting LCA studies on mix designs evaluated under practical conditions.

The competing research organisations could include research teams investigating recycled waste, such as recycled glass and CR, in concrete applications at other Australian Universities. The industry competitors could include consulting firms and contractors using low-carbon concrete in infrastructure projects and employing recycled materials in concrete in commercial projects.

c) How did you validate your outputs and measure success? How did you define that your outputs were successfully delivered? Was it based on performance? Feasibility/viability/desirability? What were the metrics your tests were measured against? Were they based on an existing benchmark or industry standard? Be specific and measurable.

The key properties of the developed concrete mixes are presented in the table below. The outputs of this project are validated through concrete performance and environmental metrics. The success of the outputs is defined as achieving equivalent or superior strength requirements specified in residential pavement standards while reducing GHG emissions, natural aggregate consumption, and landfill use compared to conventional OPC concrete.

Properties	**Control**	**PET-CR**	**HDPE**	**CR**	**PET**
Slump (mm)	170	210	200	180	175
Apparent air-content (%)	2.65	6.00	3.70	4.35	3.05
Mass per unit volume (Fresh) (kg/m^3)	2410	2335	2425	2370	2370
Mass per unit volume (Hardened) (kg/m^3)	2294	2166	2273	2362	2265
f_{cm} Mean compressive strength (@ 28 days) (MPa)	32.7	20.1	34.5	30.1	33.9
E_c Mean modulus of elasticity (@ 28 days) (GPa)	32.1	22.7	24.2	29.7	29.3
$f_{ct.f}$ Mean flexural tensile strength (@ 28 days) (MPa)	5.5	3.9	4.4	4.9	4.7
$f_{ct.sp}$ Mean splitting tensile strength (@ 28 days) (MPa)	3.4	2.1	3.2	2.9	3.1

Electrical resistivity (@ 28 days) (kΩ·cm)	57.7	71.9	37.5	48.6	49.3
Ultrasonic pulse velocity (@ 28 days) (m/s)	4579	4744	4397	4192	4265
Apparent volume of permeable voids (@ 28 days) (%)	16.28	22.01	16.54	21.72	16.54
Mean carbonation depth (@90 days) (mm)	18	18	19	14	18
Mean charge passed by RCPT (@90 days) (Coulombs)	450.38	580.02	591.77	887.55	765.14
ε_{csd} Drying shrinkage strain (@ 90 days) (με)*	653.1	1091.7	883.6	779.2	988.9
ε_{csd} Drying shrinkage strain (@ 180 days) (με)	753.3	1263.7	856.4	847.9	1021.2
ε_{csd} Drying shrinkage strain (@ 365 days) (με)	810	1292	835	785	1031
$\varphi_{\cdot ccb}$ Basic creep co-efficient (@ 90 days)	1.88	2.20	-	1.88	-
$\varphi_{\cdot ccb}$ Basic creep co-efficient (@ 180 days)	2.17	2.59	-	2.17	-
$\varphi_{\cdot ccb}$ Basic creep co-efficient (@ 365 days)	2.87	3.10	-	2.55	-

*This value represents the average drying shrinkage, calculated from measurements that fall within ±40 microstrain of the median, in accordance with AS 1012.13. [15]

The success of the concrete properties is evaluated against the requirements of AS 3727.1 [14] and VicRoads 703 [16] for residential pavements. A comparison was made between the developed mixes in this project and normal-class concrete (grade N) as specified in AS 1379 [17]. The PET-CR mix is most similar to N20 concrete, while the other mixes are comparable to N25 concrete. However, due to the inclusion of lightweight particles and high slump, these mixes cannot be classified as "N" concrete. Instead, they can be considered special-class concrete (S20 and S25), suitable for pavements intended for pedestrian-only or pedestrian and light vehicle traffic, as outlined in AS 3727.1 [14].

The workability and performance of the developed mix in large-scale practical applications were measured by the success of field trials for footpath applications. Feedback from contractors indicated that the performance of the developed mixes (PET-CR and Control) is on par with that of OPC concrete. Long-term performance is being monitored through regular visual inspections, which have shown clear broom finishing and no significant distress at 90 days.

To evaluate the performance of the up-scaled concrete mixes used in the field trials, i.e., Control and PET-CR, interlaboratory tests were conducted to assess slump, compressive strength, flexural strength, and drying shrinkage. The comparative results are presented in Figures 1-3. In these figures, "Control" and "PET-CR" refer to specimens cast at RMIT University and tested by PhD student, whereas "Control_Hanson" and "PET-CR_Hanson" were cast at the Hanson laboratory (Clarinda) and tested by the Hanson technical service team. Additionally, "Control_Site" and "PET-CR_Site" were cast on-site during the field trial and tested by the Hanson technical service team.

A reduction in slump was observed in both mixes on-site, likely due to the weather conditions (windy and humid) that accelerated moisture evaporation on pouring day. The higher compressive strength recorded for the site-cast specimens may also be attributed to increased evaporation, resulting in a lower effective water-to-binder ratio. Variations in drying shrinkage results across different laboratories may be influenced by differences in initial exposure conditions or measurement precision. More discussions will be presented in journal papers and PhD thesis. Nevertheless, all test results indicate that the shrinkage performance meets the requirements for N20 concrete, with drying shrinkage remaining below 1000 micro strain at 56 days [17].

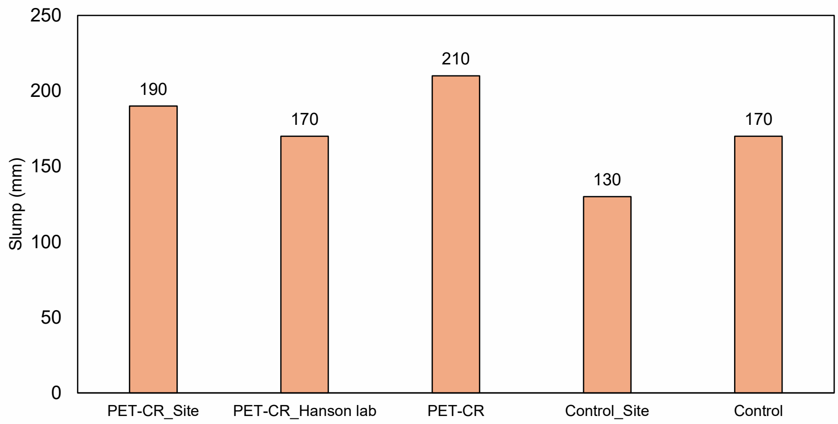


Figure 1. Slump of mixes

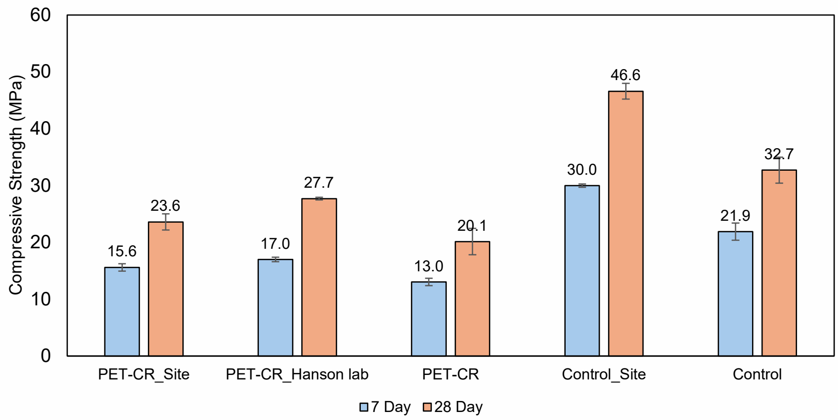
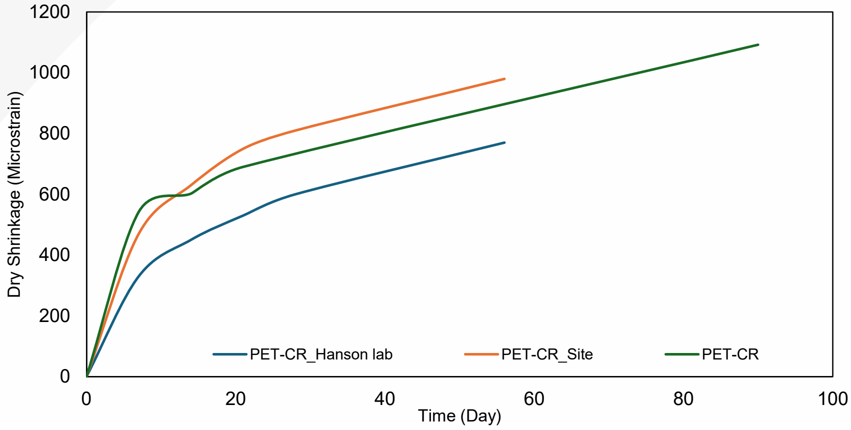


Figure 2. Compressive strength of mixes



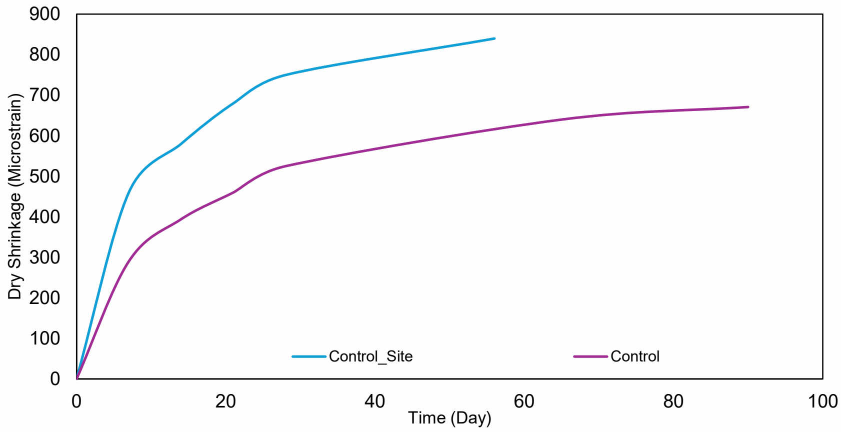


Figure 3. Dry shrinkage of mixes

The environmental impact of the developed concrete is assessed in comparison to OPC concrete (the reference concrete) suggested in the Green Star concrete guide [11] at a similar strength level. The table below summarizes the GHG emissions, natural aggregate reductions, and landfill savings per cubic meter of concrete. For 20 MPa concrete, the developed PET-CR mix results in a reduction of 94 kg/m^3 (0.03 m^3/m^3) (33.57%) in cement usage compared to the reference concrete (R20) due to the replacement of cement with GGBFS. Natural fine aggregate usage is reduced by 38.38% by weight (46.63% by volume), contributing to a 5.35% reduction in GHG emissions. Additionally, 120 kg/m^3 of recycled waste materials (PET and CR) were incorporated, saving 0.114 m^3 of landfill space.

For 32 MPa concrete, cement usage is reduced by 174 kg/m^3 (0.06 m^3/m^3) (48.33%) relative to the reference concrete (R32). The reductions in natural aggregate usage are as follows: 29.48% by weight (27.37% by volume) for Control, 29.78% by weight (28.24% by volume) for HDPE, 33.38% by weight (36.72% by volume) for CR, and 33.41% by weight (37.27% by volume) for PET. These reductions result in GHG emission decreases of 25.18%, 25.67%, 26.16%, and 30.56% per cubic meter, respectively.

Mix ID	Natural aggregate (kg/m^3)	Cement (kg/m^3)	GHG (kgCO_2-e/m^3)	Recycled waste materials (kg/m^3)	Landfill saving (m^3)
R20	1978.0	280	318	0	0
PET-CR	1210.0	186	301	120	0.114

R32	1870.0	360	409	0	0
Control	1430.2	186	306	0	0
CR	1323.2	186	302	60	0.056
HDPE	1415.4	186	304	5	0.005
PET	1316.9	186	284	60	0.059

The costs of the developed concrete mixes per cubic meter are as follows: $181.88 for the control mix, $202.26 for PET, $202.79 for CR60, $183.86 for HDPE, and $223 for PET-CR. The higher costs, particularly for the PET and CR mixes, are due to the significantly higher prices of CR and PET, which are around $500 per tonne—substantially more expensive than natural aggregates. However, it is anticipated that these costs will decrease as demand increases and regulatory frameworks continue to mature.

The continuous recycling of concrete materials has been studied to assess their recyclability. In particular, the PET-CR concrete mixture was crushed to a particle size of 7 mm for use as a replacement for natural coarse aggregate. An experimental plan was developed to evaluate the effects of incorporating recycled concrete aggregates (RCA) with CR and PET. Two new mix designs were developed: PET-CR-2RCA54 and PET-CR-2RCA100. These mixes represent the second generation of concrete and replace the 7 mm natural coarse aggregate, with PET-CR-2RCA54 substituting 54% and PET-CR-2RCA100 replacing 100% by volume. Once the performance of the second-generation mixes was assessed, the concrete was crushed again and processed into 7 mm aggregates, which were then reused to cast the mixes once more and evaluate their performance. This set of mixes is referred to as third-generation concrete, denoted as “3RCA” in the table below. The main properties of the developed concrete mixes are shown in the table below. The results show the potential of the PET-CR concrete mixture to be reused as RCA.

Properties	PET-CR-2RCA54	PET-CR-2RCA100	PET-CR-3RCA54	PET-CR-3RCA100
Slump (mm)	55	179	54	45
Apparent air-content (%)	7.9	8.2	9	5.8
Mass per unit volume (Fresh) (kg/m^3)	2098	2040	2068	2103
Mass per unit volume (Hardened) (kg/m^3)	2128	2063	2100	2111

f_{cm} Mean compressive strength (@ 28 days) (MPa)	22.4	19.5	19.2	20.4
E_c Mean modulus of elasticity (@ 28 days) (GPa)	21.6	19.3	23.8	21.7
$f_{ct.f}$ Mean flexural tensile strength (@ 28 days) (MPa)	4.3	3.5	3.7	3.8
$f_{ct.sp}$ Mean splitting tensile strength (@ 28 days) (MPa)	2.5	2.1	2.5	2.5

d) What kind of engagement with the concrete industry was conducted throughout project delivery with relevant customers, end users, supply chain participants and relevant industry/government bodies to ensure awareness and feedback?

The project engaged with the concrete industry through collaboration with DM Roads (contractor), Hanson (material supplier), and Mornington Peninsula Council (end-user) during field trials. This ensured the practical applicability of the developed mixes, including efficient concrete delivery and the assessment of workability and performance. Quarterly steering meetings with SmartCrete CRC, OPV, and the research team helped guide the project's direction and monitor progress. Visits to Hanson’s technical service team and collaboration with their laboratory were instrumental in testing and adapting the concrete mixes for footpath applications.

An industry event, organised by Prof. Gravina at the University of Queensland, provided an opportunity for knowledge sharing and exchange. Additionally, SmartCrete CRC hosted a community talk to discuss the feasibility of the developed mix with the public. Regular interactions with industry visitors also played a key role in raising awareness about the use of recycled materials in concrete, promoting GHG emission reductions, and fostering ongoing knowledge exchange.

4. Analysis of Key Results, Deliverables, Description of Outputs and Project IP

Governance	Contracted	Achieved / Actuals
Deliverables	1. Optimised concrete mix formulations with combinations of recycled materials 2. Experimentally determine workability, mechanical strength and abrasion testing 3. Pavement field trials in several local councils 4. Visual inspections 5. The publication of research results and standard/mix design 6. Guideline for contractors and performance requirements for concrete with recycled material 7. Investigation into continuous recycling concrete with recycled material (PhD program)	1. Achieved, with successful development of mixes incorporating recycled materials. 2. Achieved, with comprehensive testing of the developed mixes for workability and performance. 3. Achieved, with field trials conducted in collaboration with local councils to assess real-world applicability. 4. Achieved, with regular inspections conducted to evaluate long-term performance and detect any distress. 5. Final write-up stage 6. Achieved, Performance requirements for concrete footpath with recycled materials. 7. Final write-up stage titled multi-functional unit-based life-cycle assessment of sustainable concrete containing recycled waste materials No additional deliverables were added to the project.
Intellectual Property	N/A	N/A

The key outcomes of this project include (1) optimised concrete mixes, (2) comprehensive long-term experimental data, (3) successful demonstration of footpath applications, (4) a thorough life cycle assessment, (5) a guideline for using recycled materials in concrete, and (6) experimental data on the regeneration of the developed concrete mixes.

The project demonstrated the feasibility of incorporating recycled materials into concrete while maintaining performance comparable to traditional OPC mixes. Notable achievements include significant reductions in cement use, natural aggregates, and GHG emissions. These results confirmed the hypothesis that using recycled materials in concrete can lower environmental impact without compromising workability or performance for non-structural applications.

Successful field trials for footpath applications validated the practicality of the developed mixes, addressing concerns about large-scale implementation and supporting the assumption that industry adoption is viable. The project also helped tackle key industry challenges, such as the scarcity of natural aggregates, high carbon emissions, and landfill pressures. By integrating recycled materials, the project offers practical solutions that reduce dependence on virgin resources, mitigate environmental impacts, and promote more sustainable concrete production. Furthermore, collaboration with industry stakeholders ensured that the project's outcomes aligned with real-world needs.

5. Next Steps – Commercialisation & Impact Plan

Long-term operation of and access to research outcomes and outputs

Consideration	At project close	Longer term
Handover of outputs	1. Published journal papers - Mechanical and durability performance of waste-based concrete (In preparation) - Life cycle assessment of waste-based concretes: a cradle to grave model (In preparation) - Durability properties and regeneration capability of waste-based concretes (In preparation) 2. Guideline 3. PhD thesis	The journal papers and PhD thesis, which will contain all the experimental data, LCA results, and detailed methodologies and analysis, will require preparation for peer review and publication process before handover.
Hosting of project outputs	All experimental data and analyses will be in journal paper format and available online for all project partners. Prof. Gravina can be contacted for any information required.	The outputs will be in journal paper format and available online for the public.
Project data, materials and equipment	The raw data will be kept by Prof. Gravina. The experimental results and analyses will be in the form of journal papers and available online.	The raw data will be kept by Prof. Gravina, and all the results will be in the form of journal papers that are available online.
IP management	No action is needed.	No further action is needed.
Commercialisation	The immediate step is to share the guideline with industry stakeholders, enabling the developed concrete mixes to be directly applied as S20 or S25 concrete for footpath applications. At this stage, the research team will finalise the journal paper manuscript for peer review, while industry partners can	The main steps for longer-term go to market plans are as follows • Footpath trials • Market analysis • Environmental, safety, and health investigation • Development of practical construction guidelines

	offer additional feedback on the guideline.	• Large-scale applications • Refinement of guidelines • Market strategy and plan • Legal matters and risk management Details of these activities can be found in the table in Section 2.

6. Education and Training

The concrete mixes developed in this project were designed to align with existing mixing, curing, and casting procedures, making them ready for immediate practical use. However, a standard batch plant conveyor system is not designed to transport PET and CR directly from their storage to the mixer. The PET and CR would need to be pre-weighted and manually dosed into the mixer. Apart from that, no new technologies, equipment, installation processes, or construction methods are necessary. The guideline offers recommendations for incorporating recycled materials into concrete for construction practices. Led by Prof. Gravina, the research team can take on the role of educators, with contractors being the primary target audience for training. The most effective approach would involve on-site instruction from educators, although the guideline itself would be sufficient for users.

The PhD thesis will be submitted by the end of June 2025. The thesis is directly linked to the project, with an experimental program conducted to evaluate the performance of various mix designs and gain a deeper understanding of waste-based concretes. These findings have been instrumental in enabling the field trial and advancing knowledge on the incorporation of recycled waste aggregates into concrete. The PhD student has presented his work on multiple occasions throughout the program, including at the Smartcrete Breakfast, the UQ Three Minute Thesis Competition, the UQ Civil HDR Conference, and the 2023 Concrete Conference. Upon completion of the PhD, the student intends to pursue an academic career and has potential opportunities to obtain a postdoctoral position, continuing research in concrete sustainability.

7. Conclusions, Implications and Recommendations

This project addressed several key challenges: (1) incorporating recycled waste materials into concrete to reduce landfill waste, (2) decreasing the consumption of natural aggregates and cement to conserve quarry resources and lower GHG emissions, and (3) developing concrete mixes that meet these objectives while being suitable for large-scale construction. The remaining challenge is to reduce the overall cost of recycled waste-based concrete, as the high cost of materials like PET and CR remains a limiting factor.

A major achievement of this project is that the developed concrete mixes surpassed initial expectations. The assumption was that waste-based concrete could reduce natural aggregate by 20% by weight and cut GHG emissions while maintaining similar strength. In reality, all "S25" concrete mixes reduced natural fine aggregate by over 29.48% by weight (27.37% by volume) and cut GHG emissions by more than 25%. The “S20” concrete mix (i.e., PET-CR mix) reduced natural fine sand by 38.38% by weight (46.63% by volume). Another key success was the on-site application of the PET-CR mix for footpaths, demonstrating its feasibility for construction.

Key learnings from this project include:

- Effective integration of recycled materials requires careful mix design and testing to balance sustainability and mechanical performance.
- Collaboration with contractors and suppliers is crucial for adapting mixes to practical applications and overcoming real-world challenges.
- Successful on-site trials underscore the importance of validating laboratory results in real-world conditions.
- Well-defined performance guidelines are essential for promoting the adoption of developed mixes and ensuring their consistent application.

Future research recommendations include investigating:

- Potential environmental concerns such as soil contamination and microplastic issues.
- Identifying possible health risks associated with recycled materials.
- The long-term degradation of concrete under varying climatic and environmental conditions.
- The standardization of low-carbon concrete incorporating waste, considering environmental impacts at the design stage.
- A detailed microstructural analysis of pore characteristics in recycled waste-based concrete.
- Predictive models for shrinkage and creep in recycled concrete.

8. Publication List

Vaca, A.A., Wang, Y., Xie, T. and Gravina, R. (2023). Life-Cycle assessment of sustainable concrete containing recycled waste materials. Concrete 2023 - The 31st Biennial National Conference of the Concrete Institute of Australia

Mechanical and durability performance of waste-based concrete (In preparation)

Life cycle assessment of waste-based concretes: a cradle to grave model (In preparation)

Durability properties and regeneration capability of waste-based concretes (In preparation)

Multi-functional unit-based life-cycle assessment of sustainable concrete containing recycled waste materials (PhD thesis in preparation)

9. Acronyms and Abbreviations

ACCU	Australian Carbon Credit Unit
CR	Crumb rubber
f'_c	Characteristic compressive strength
f_c	Mean compressive strength
f_{cm}	Mean compressive strength tested at 28 days
GGBFS	Ground-granulated blast-furnace slag
GHG	Greenhouse gas
HDPE	High-density polyethylene
ISO	International organisation for standardisation
LCA	Life cycle assessment
OPC	Ordinary Portland cement
OPV	Office of Projects Victoria
PET	Polyethylene terephthalate
SCMs	Supplementary cementitious materials

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11. Appendix –Thesis structure

THE UNIVERSITY OF QUEENSLAND

AUSTRALIA

Multi-functional unit-based Life-Cycle Assessment of sustainable concrete containing recycled waste materials

Alvaro Daniel Amezquita Vaca

Bachelor in Civil Engineering

Master of Engineering (Civil Engineering)

0009-0005-7311-8469

A thesis submitted for the degree of Doctor of Philosophy at

The University of Queensland in 2025

School of Civil Engineering

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