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The Utilisation of Products with Recycled Content in Construction Projects to Combat Urban Heat Island Effects

ABSTRACT

The architecture, engineering and construction (AEC) sector significantly contributes to carbon emissions worldwide. Environmentally responsible improvements in this sector will result in carbon emission reduction and mitigate the impacts of global warming and urban heat island (UHI). Circular economy (CE) is a major initiative that has recently gained momentum. This initiative aims to improve resource efficiency and circularity in the AEC sector through various strategies including the application of products with recycled content (PwRC). Such a circularity in resources assists the AEC sector in significantly reducing its carbon emissions and improving undesired thermal exchange in cities. To better understand this relationship, this study explored PwRC thermal performance that may positively contribute to mitigating UHI effects. Furthermore, the study investigated how relevant stakeholders perceive this benefit when procuring PwRC in Australia. The results showed that some PwRC can be used as an effective countermeasure to tackle UHI issues in cities. However, the analysis of stakeholders' perceptions suggested that in Australia the adoption of PwRC is barely associated with or driven by their ability for reducing UHI effects in cities.

Keywords: Construction and demolition waste, circular economy, built environment; Australia; carbon emissions

Introduction

Urban Heat Island (UHI) refers to the phenomenon where urban areas are significantly warmer than their surrounding rural areas. This is due to the absorption of heat by man-made materials such as concrete, asphalt, and buildings, as well as the lack of vegetation and water bodies in cities (Oke, 1982). UHI can have a significant impact on people's lives in cities, particularly during heat waves. In addition, UHI can also affect the air quality in cities, as higher values of temperature can increase the concentration of pollutants in the air (Akbari and Rosel, 2008). The latest reports on UHI predict that this phenomenon will be increased in both intensity and frequency (IPCC, 2022). The increasing consumption of raw materials in various sectors, especially in the Architecture, Engineering and Construction (AEC), has caused several environmental issues (Borinaga-Treviño *et al.*, 2021) such as UHI. The AEC sector consumes around 36% of global energy and thus has a significant impact on the environment (Santamouris and Vasilakopoulou, 2021).

Traditionally, mitigation of HI effects is tied with strategies such as increasing green spaces, implementing cool roofs and pavements, and enhancing public transportation to reduce road traffic and anthropogenic heat (Rosenzweig *et al.*, 2006).

Circular economy (CE) has emerged as a significant initiative in recent years, aiming to enhance resource efficiency and sustainability in the AEC sector through various strategies, including the integration of products with recycled content (PwRC) in construction projects. By fostering circularity in resources, the AEC sector can achieve notable reductions in carbon emissions, effectively manage construction and demolition (C&D) waste, and potentially mitigate undesired thermal exchange resulting from hard surfaces in urban environments.

The former deals with the use of PwRC having improved thermal performance that may be leveraged to address UHI issues by adjusting the heat exchange in urban areas. The use of PwRC may save energy consumption that would have been otherwise required for the production of new materials made of virgin materials. Furthermore, less energy consumption is a synonym for carbon emission reduction. This study aims to explore how some PwRC can contribute to mitigating UHI effects and how relevant stakeholders perceive this benefit in Australia.

Methodology

Research Design

This study employed a mixed-method approach using secondary data. The literature review was used as the data collection method. The data collection involved two steps: firstly, analysis of interview responses that were gathered in two national research projects conducted in Australia (qualitative data) and secondly the analysis of scientific publications to document the thermal performance of PwRC in comparison with their virgin alternatives (quantitative data).

Data Collection

In the first step, the interview responses that were gathered in two research projects were analysed. The focus of these projects was on the development of end markets for PwRC in Australia (Shooshtarian *et al.*, 2022a) and the application of PwRC in four Australian construction projects (case studies) (Shooshtarian *et al.*, 2023).

In the second study the case studies that were used were Burwood Brickworks Shopping Centre and Mordialloc Freeway in Victoria and the Tonkin Gap Project and OneOneFive Hamilton Hill in Western Australia. They comprise two road projects, a shopping centre and a housing development. One goal of these projects is to showcase the possibilities for using PwRC in the construction industry.

The participants who took part in these two studies were 43 experienced individuals operating across PwRC supply chains in the AEC sector. The analysis of interview data aimed to explore the perception of these stakeholders about the thermal benefits of PwRC when used on urban surfaces. The profile of 27 research participants in the first study is shown in Figure 1. Table 2 summarises profiles of 16 interviewees in the second study.

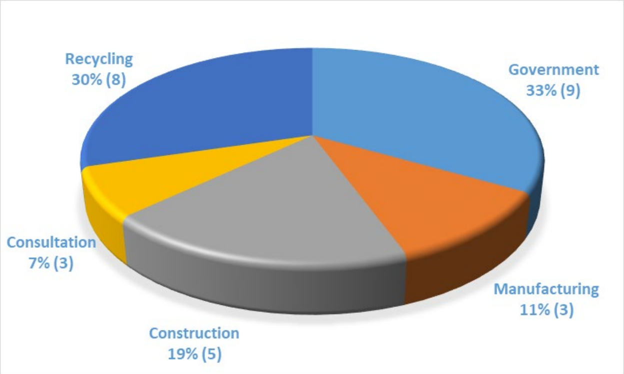

Figure 1. Research participants profile in the first study. Source: Shooshtarian *et al.* (2022a)

Table 1. Summary of the research participants in the second study.

Case study / Participant	Client	Head-contractor	Designer	Supplier
Case Study 1 (Brickworks shopping centre)	C_1P_1- 20 years' experience in construction project development	C_1P_2- About six years' experience in the organisation	C_1P_3- 11 years' experience in architectural management	C_1P_4- seven years' experience in the organisation as the sale manager
Case Study 2 (Mordialloc freeway)	C_2P_1- Senior project manager with extensive experience in project managing public infrastructure projects	C_2P_2- 20 years' experience in the construction industry as a site engineer, project engineer and manager	C_2P_3- 15 years' experience working as a design consultant	C_2P_4- Highly experienced corporate communicator with a background in government, corporate, industry and community organisations, with a four-year employment history in the organisation
Case Study 3 (Tonkin Gap Highway)	C_3P_1- Experienced sustainability advisor responsible for overseeing projects and initiatives using or promoting the PwRC application	C_3P_2- Four years' experience in the construction industry with a focus on major road infrastructure projects in the organisation	C_3P_3- 18 years' experience in the organisation and was involved in the project as the technical director and oversaw the structural design of the work	C_3P_4- Has worked in the organisation as the director since its establishment 10 years ago
Case Study 4 (OneOneFive Hamilton Hill)	C_4P_1- A senior development manager involved in the property industry for more than 30 years	C_4P_1- A civil engineer and the director of the organisation with 20 years' working experience in the organisation	C_4P_3- The director of a private company that specialises in landscape architects, urban design and sustainability consultancy	C_4P_4- The director of the organisation with more than 27 years' experience in waste recovery in Western Australia

The second step of the literature review involved the analysis of extant literature to identify the thermal benefits of PwRC compared to conventional materials. Furthermore, it reviews and compares the carbon emissions during the production of conventional materials with their recycled alternatives to document the carbon-saving benefits of PwRC. The literature review process was inspired by 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)' (Figure 2) as described by Moher *et al.* (2009).

The literature reviewed included scientific peer-reviewed articles that were captured in Scopus and Web of Science databases with a date range of 2012 to 2023. The search keywords included 'thermal performance', 'recycled material', and 'recycled construction material'.

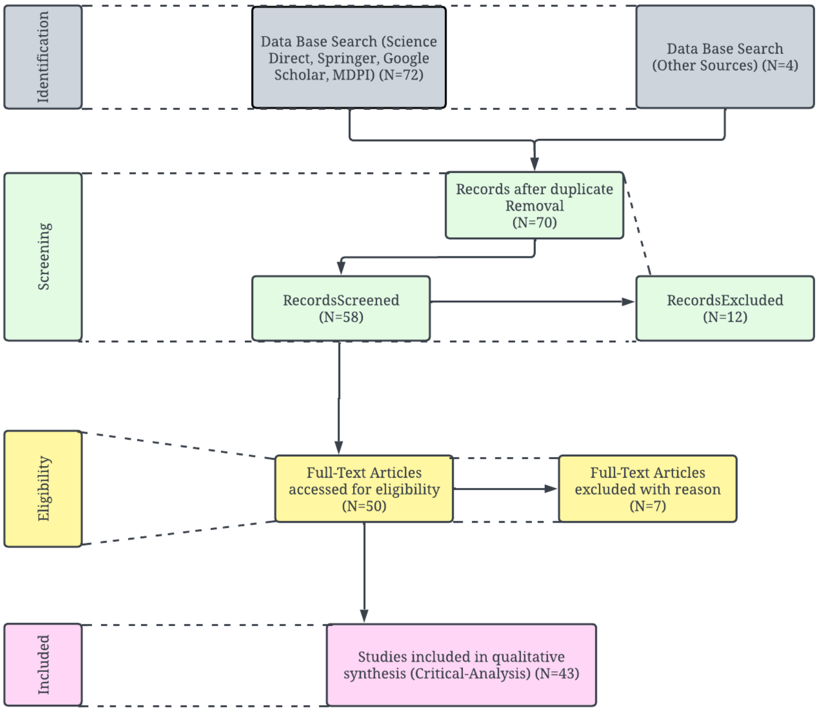

Figure 2. PRISMA flow diagram; *Source:* adapted from Moher *et al.* (2009)

Results

Step 1: Analysis of Australian Stakeholders: PwRC Thermal Performance

This analysis was conducted to understand whether Australians consider PwRC thermal benefits when procuring them for construction projects. The secondary data were captured from two research studies that were conducted by the authors. In the first study (2020-2021), out of 43 responses to a question enquiring about primary enablers of PwRC end-markets development (Shooshtarian *et al.*, 2022a), only four factors were related to environmental impacts and two factors were relatively linked to the thermal benefits of PwRC: (1) *valuing waste material as an input, that is making a significant contribution to reducing both emissions & resource usage*, (2) *increase the knowledge of recycled products: risks & benefits*. The majority of other enablers were regulatory, technical, and economic in nature. One year later, in the second study (2022-203), 16 key stakeholders of four construction projects were asked about the main reasons for using PwRC. Out of 64 factors deemed to motivate the use of PwRC, '*environmental benefits*' (n=13) had the highest rank followed by *'ensuring the competitive advantage & future proofing'* (n=9) (Figure 3).

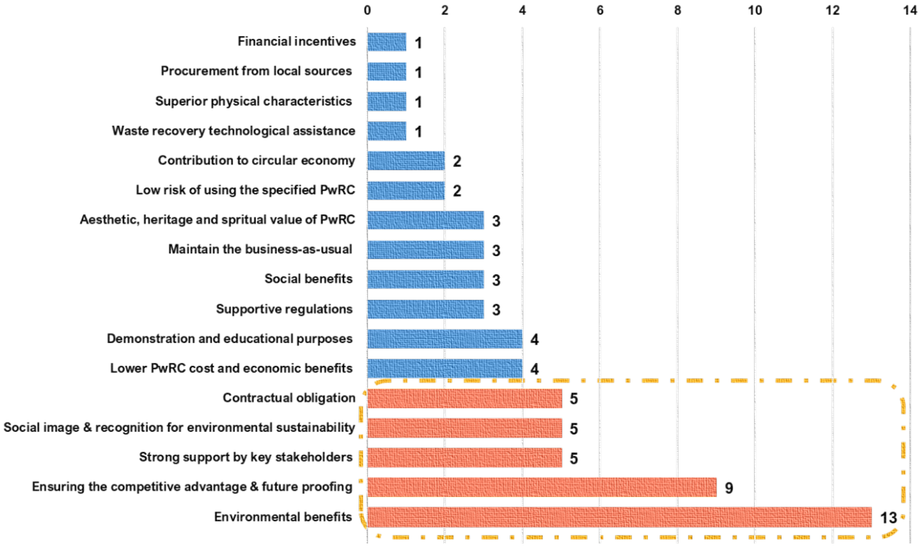

Figure 3. The distribution frequency of the main motivations categories for using PwRC. Source: Authors

This category, representing about 17% of the total motivation factors, consisted of several sub-factors including '*reduced carbon emissions*', '*less waste landfilling*', '*project vision to be green*', '*solving the issue of PwRC stockpiling*' and '*reducing virgin material extraction*'.

Step 2: Analysis of Peer-Reviewed Articles: Descriptive Findings

The study utilised the PRISMA technique to collect relevant and up-to-date data on the thermal performance of PwRC for improved thermal exchange in urban areas. Most of the publications captured through the PRISMA process were published as journal articles (92%). As shown in Figure 4, around 60% of these were published after 2019, indicating the importance of climate change-resilient built environments in the current research agenda.

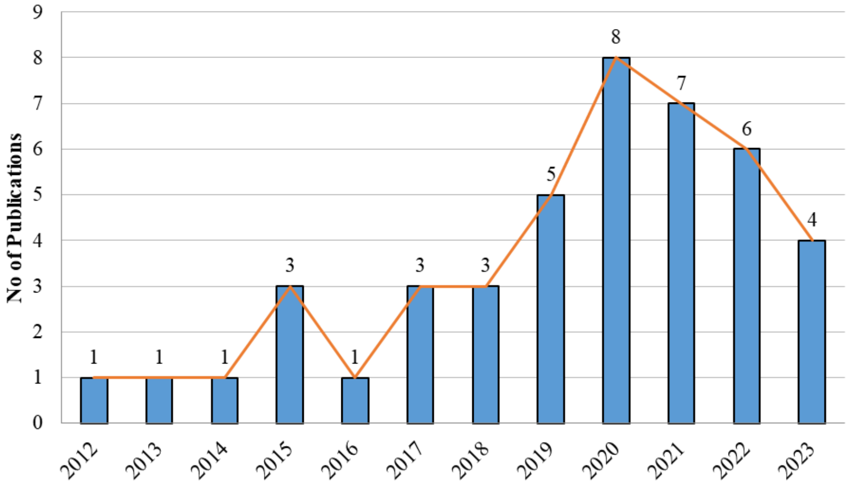

Figure 4. Distribution of publication year for the reviewed articles in this study. Source: Authors

According to the descriptive analysis, the highest number of journal articles were published in *Construction and Building Materials*, *Journal of Building Engineering*, and *Energy and Building*. In terms of the geographical distribution of these resources, the highest number of them was published by scholars from China, followed by that from Italy and Spain (Figure 5). This geographical distribution shows that this area of research is new to various parts of the world.

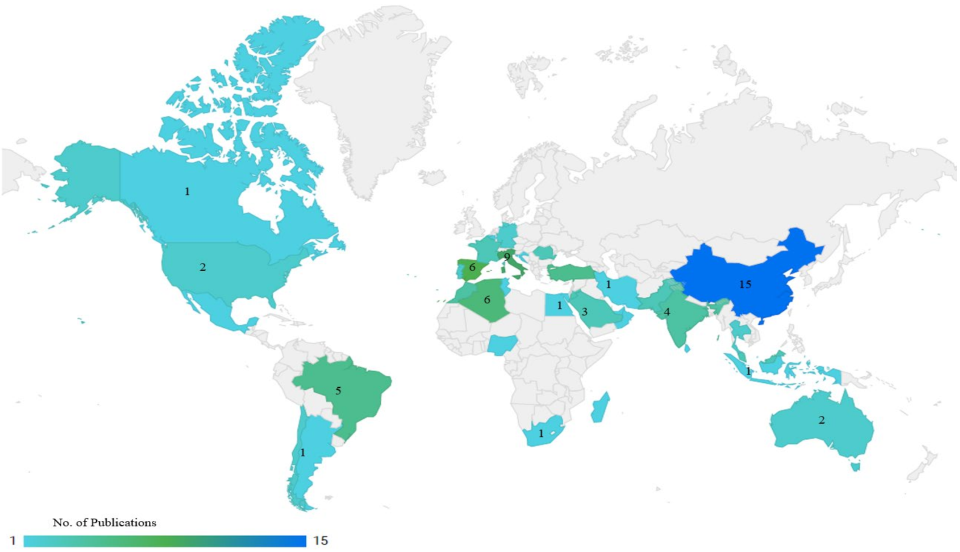

Figure 5. Visual representation of the geographical distribution of research outputs. Source: Authors

Thermal Benefits of PwRC

In order to evaluate PwRC thermal performance two thermal indicators were used. These include thermal conductivity and heat transfer coefficient which determine material heat exchange with the surrounding environment (Mascaraque *et al.*, 2021). Thermal conductivity (K) is one of the key parameters of thermal performance and its lower values signify reduced heat transfer and thus is beneficial to areas with high UHI intensity. For instance, the K value of concrete with 30% recycled plastic aggregates is 0.71 (W/mK), suggesting that it can better resist heat transfer compared to that of conventional porous concrete which K is 1.35 (W/mK). Similarly, the Heat Transfer Coefficient (U) defines the heat transfer properties of materials. The lower value of the heat transfer coefficient for materials can contribute to UHI mitigation. Table 2 presents evidence that supports the notion that PwRC exhibits enhanced thermal performance when compared to conventional materials, particularly in the context of mitigating the UHI effect. The observed differences in thermal conductivity between RwPC and conventional materials are noteworthy, with the former demonstrating values ranging from 1.59 to 2.75 times greater than those of their conventional counterparts. Specifically, recycled concrete was found to exhibit a 1.59 times higher thermal conductivity than conventional concrete (Afsarian et al., 2018), while sand in PwRC exhibited a 2.75 times greater thermal conductivity than sand screed (Alani et al., 2012).

Table 2. Thermal properties of PwRC and virgin materials; Source: Authors

Type	**Conventional material**	**Thermal properties** (W/mK)	**PwRC**	**Thermal properties** (W/mK)	**Reference**
Bricks	Bricks with 0% waste plastic, 15% OPC, 15% fly ash, and 70% sand	TC: 0.81	Bricks with 10% waste plastic (Polystyrene), 15% OPC, 15% fly ash and 60% sand	TC: 0.4	Mondal *et al.* (2019)
Concrete	Conventional or porous concrete	HTC 3.03 TC: 1.35	Concrete with 50% recycled brick aggregates	HTC: 0.55 TC: 0.74	Afsarian *et al.* (2018)
			Concrete with 50% of recycled concrete aggregates	HTC: 0.55 TC: 0.85	
			Concrete with 30% recycled plastic aggregates	HTC 0.55 TC: 0.71	Colangelo *et al.* (2013)
	Plain concrete	TC: 0.65	Aggregate replacement by Fibers fixed to crumb rubber (FCR)	TC: 0.34	Medina *et al.* (2017)

Insulation Sheets/ Panels	Conventional thermal insulation panel	TC: 0.16	Thermal insulation panel using recycled cardboard & Corn-starch binder	TC: 0.06	Şova *et al.* (2018), Mathews *et al.* (2023)
			Recycled textile fibres in thermal insulation sheets	TC: 0.04-0.05	Tallini and Cedola (2018)
Sand	Sand screed	TC: 2.2	Recycled Glass Screed (Alpha Hemihydrates)	TC: 0.8	Alani *et al.* (2012)

TC: Thermal Conductivity, HTC: Heat Transfer Coefficient

The analysis of the heat transfer coefficient revealed a substantial difference between plain concrete and concrete incorporating recycled plastic aggregates, with the latter exhibiting values up to 5.5 times greater than those of the former (Colangelo et al., 2013).

Carbon Saving by Products with Recycled Content

The carbon emissions associated with the application of materials in construction projects are the product of energy consumed during the production, transportation, installation, maintenance, and disposal of the material. There are various models to calculate the carbon emissions of a product or system, the most commonly used is life cycle assessment (LCA) in which products are systematically assessed during their life cycle at every stage (Pandey *et al.*, 2011). Hence, its estimation is highly dependent on the assumptions, defined boundaries, scope, and methodologies used (Fenner *et al.*, 2018). Table 3 shows the comparison of carbon emissions by the use of virgin materials and alternate PwRC in the construction industry.

Table 3. Carbon emissions from virgin and recycled construction materials; Source: Authors

Type	**Conventional material**	**CO$_2$ emissions**	**PwRC**	**CO$_2$ emissions**	**Reference**
Aggregates	Natural aggregates	234 kg CO$_2$-e/m^3	Recycled aggregates	65.7 kg CO$_2$-e/m^3	Momotaz *et al.* (2023)
Concrete	Concrete with 0.5w/c ratio and natural aggregates	350.7 kg CO$_2$-e/m^3	Concrete with 0.7 w/c ratio and 100% recycled aggregate	261.4 kg CO$_2$-e/m^3	Jiménez *et al.* (2018)
	Concrete with natural aggregates	469.26 kg C$_e$/m^3	Concrete with 22% recycled aggregate	432.15 kg C$_e$/m^3	Xiao *et al.* (2018)
	Concrete with natural coarse and fine aggregates	382.99 kg CO$_2$/m^3	Concrete with 1.36% replacement of fine aggregates with PET waste	-379.48 kg CO$_2$/m^3	Zuraida *et al.* (2021)
Roads	Use of virgin materials in CRB[a] for conventional 100-m road section.	180-ton CO$_2$-e /100-m	Use of RCR[b] in subbase and base in replacement of CRB in a 100-m road section	174.9-ton CO$_2$-e /100-m	Biswas (2014)
	Asphalt concrete for the binder and base layer without RAP[c]	95 kg CO$_2$-e/ton	Asphalt concrete for the binder and base layer with 93% RAP[c]	35 kg CO$_2$-e/ton	Bizarro *et al.* (2021)
Cement	Ordinary Portland cement	0.78-ton CO$_2$/ ton-OPC	Recycled cements by burning old OPC waste at 450°C	0.05-ton CO$_2$/ ton RC-450	He *et al.* (2019)
Aluminum	Virgin aluminum for buildings	3.16 kg CO$_2$/kg aluminum	Recycled aluminum for buildings	0.73 kg CO$_2$/kg recycled aluminum	Shafiq *et al.* (2015)
Steel	Virgin mild steel	1.19 kg CO$_2$/kg mild steel	100% recycled mild steel	0.19 kg CO$_2$/kg recycled mild steel	Gardezi *et al.* (2015)
	Virgin steel rebars	2.68 kg CO$_2$/kg	100% recycled steel rebar	0.42 kg CO$_2$/kg steel rebar	

		steel rebar			
	Reinforced steel	1.33-ton CO_2-e/ton steel	Recycled reinforced steel	0.37-ton CO_2-e/ton steel	Yan *et al.* (2010)

[a] Crushed Rocked Base, [b] Recycled Concrete Rubble, [c] Reclaimed Asphalt Pavement

The examination of relevant literature indicates that significant carbon savings can be attained through the production of PwRC. The documented variations in carbon savings are considerable, ranging from as modest as 1.04 times higher when crushed rock is replaced with recycled concrete rubble (Biswas, 2014) to as much as 15.6 times greater when conventional cement is replaced with recycled cement (He *et al.*, 2019). Interestingly, one study (Zuraida *et al.*, 2021) reported that carbon emissions net balance for concrete with 1.36% replacement of fine aggregates with PET waste was negative.

Discussion and Conclusion

Extensive urbanisation has challenged the ecosystem of cities worldwide. Among various ecological challenges, UHI has proven to have a detrimental impact on residents of urban areas. Hence, scientists, studying urban heat exchange, have offered a wide array of solutions to mitigate UHI effects. Changes in urban surfaces were found to be an effective UHI countermeasure.

The research has shown that PwRC can be used to build urban surfaces with improved thermal performance. This review study provided evidence demonstrating the superior thermal performance of PwRC compared to conventional materials. Specifically, the research endeavors in this domain have expanded to tackle the acute UHI phenomenon in cities across the globe. Among different countries, China has the largest number of scientific publications followed by Italy and Spain.

The selection of PwRC with this goal in mind will deliver several environmental and economic benefits. Firstly, the use of PwRC will result in minimum waste landfilling. Secondly, it contributes to the mitigation of UHI in cities, a reason that further adds to the justification of using PwRC. Thirdly, this, in turn, will unlock market opportunities for these resources and drive further recycling and optimised application of PwRC in construction projects. Lastly, the use of PwRC contributes to creating zero net emission cities that are in alignment with climate change targets set by different countries including Australia.

Despite the growing awareness within the AEC sector regarding the environmental benefits of PwRC, the analysis of qualitative data obtained from interviews with Australian experts in this field indicates a lack of understanding regarding this specific environmental aspect of PwRC application. As such, the industry and government must collaborate to more effectively communicate this environmental advantage of the PwRC application, particularly in urban areas suffering from UHI effects. Implementation of demonstration projects and training programs can serve as valuable tools for achieving this objective (Shooshtarian *et al.*, 2022b).

In light of the current findings, it is recommended that future studies focus on conducting field experiments to evaluate the thermal performance of PwRC relative to that of conventional materials, particularly over both summer and winter seasons. This approach will provide a more comprehensive understanding of the efficacy of PwRC in mitigating the UHI effect and facilitating the design of climate-adaptive cities.

This research contributes to the theory and practice of three sectors: AEC, waste recycling and urban planning. The study provides a ground for these sectors to jointly achieve desired sustainable outcomes by investigating and driving the application of PwRC in cities as a means for UHI mitigation. In Australia, particularly, it helps the waste recovery sector to manage 29 million tonnes of C&D waste that are annually generated in the AEC sector (National Waste Report, 2020).

Furthermore, it recommends two strategies, demonstration projects and education, seeking to improve the industry's perception regarding the PwRC environmental benefits. Further research may investigate how these strategies can drive further utilisation of PwRC in highly urbanised areas. Upon establishing clear evidence of the environmental benefits of PwRC, it may be possible to develop new policies mandating their use in new construction projects. This approach has already been implemented in some areas of Sydney, Australia, where the use of dark roofs has been banned (Thompson, 2021). Such policy interventions can serve as effective tools in promoting the adoption of sustainable building practices and mitigating the negative impacts of urbanisation on the environment.

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