RESEARCH

SUSTAINABILITY ASSESSMENT OF REINFORCED CONCRETE BEAM MIXES CONTAINING RECYCLED AGGREGATES AND INDUSTRIAL BY-PRODUCTS

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ABSTRACT

A vast amount of construction and demolition (C&D) wastes are generated in Western Australia (WA) of which a major portion goes to landfills. The diversion of C&D waste from landfills would be the single most significant opportunity for WA to improve its recovery performance. C&D waste materials have already been investigated for their appropriateness and use in pavement and concrete. This work is the continuation of the authors' previous work involving further experimental tests to prove the structural suitability of a building's structural member (i.e., beam) made of recycled aggregates and industrial by-products. The concrete mixes considered in this study are 100NA+100 OPC (Control), 100RA+100OPC, 50RA+50NA+90OPC+10SF and 50RA+50NA+60OPC+30FA+10SF. The Reinforced Concrete (RC) beam made of 50RA+50NA+60OPC+30FA+10SF concrete mix was found to be the only eco-efficient option. This option has reduced the level of environmental impacts in a cost-competitive manner. The use of this eco-efficient option could also provide new employment opportunities and significant improvements in terms of land and energy resources conservation and bio-diversity enhancement.

KEYWORDS

OPC = ordinary Portland cement; NA = Natural Aggregate; RA = Recycled Aggregates; SF = Silica Fumes; FA = Fly Ash

BACKGROUND

Concrete demand in the construction sector is increasing rapidly due to rapid growth of urbanisation. A significant amount of energy intensive binding materials and aggregates is required to make concretes. The growing concern around global warming and the depletion of non-renewable, natural resources have necessitated the use of recycled waste materials as a replacement for virgin aggregates in concrete. For instance, about 19 million tonnes of construction and demolition (C&D) waste was generated a year in Australia (Hyder Consulting et al. 2011), and this quantity is increasing every year (Pickin and Randell, 2017). Over 15 billion tons of C&D wastes were generated in China in 2015 (Tai et al. 2017) and around 900 million tonnes per year in the United States, Europe and Japan (WBSD, 2009). By converting these C&D

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wastes to coarse aggregates for current and future construction, there can be a reduction in the production and consumption of natural aggregates as well as landfill areas and other associated environmental impacts. Extensive research (Guo et al. 2018; Ismail et al. 2017; Ozbakkaloglu et al. 2018; Xie et al. 2019; Pedro et al. 2018) was conducted to evaluate the fresh and hardened properties of recycled aggregates concretes. The mechanical and durability properties of concretes are found to be affected due to use of recycled aggregates. The failure behaviour and load capacity of structural members (e.g., beam, column, slab, etc.) made of recycled aggregate concretes have to be compared with members made of conventional concrete. Several researchers investigated the structural behaviour of recycled aggregates (RA) based reinforced concrete (RC) beams.

Ignjatović et al. (2018) found that beams made of 50% and 100% recycled aggregates demonstrated the same shear behaviour[2] as the natural aggregates (NA) beams for the same amount of shear reinforcement. However, Katkhuda and Shatarat (2016) found slightly improved shear capacity of the RA based RC beams compared to natural and untreated aggregates. Waseem and Singh (2016) found that there is a marginal increase in shear strength when natural aggregates were replaced by recycled aggregates (50% and 100%) for both normal (30 MPa) and high strength (70 MPa) concrete applications. The shear strength of these two concrete classes was further increased by almost 50% due to use of a higher percentage (1.28%) of transverse reinforcement.[3] Gonzalez and Martınez (2007) also compared the shear strength of concrete beams made of 50% of RA and 50% NA with conventional concrete beams by varying the transverse reinforcement for the same longitudinal reinforcement. The premature cracking and notable tensile cracks of beams were observed with little differences in deflections and ultimate load.

Few research projects investigated the shear strength of recycled aggregates concrete using fly ash, silica fume and fibres as a partial replacement for cement. Gonzalez et al., (2009) replaced 8% ordinary Portland cement (OPC) with silica fume and 50% NA with RA in order to improve the shear behaviour of RA based RC beams. Improvement in shear behaviour was observed in both concrete mixes due to the use of silica fume; the addition of silica fume was found to reduce the splitting cracks in another study (González and Martínez, 2007).

Apart from shear behaviour, several research projects were conducted to study the flexural behaviour[4] of reinforced concrete beams made of recycled aggregate concretes. They found that the deflection at an ultimate load of RC beams made of recycled aggregates concretes are smaller than those of conventional concrete beams and that there was no decrease in flexural capacity of beams made of recycled aggregate concretes. On the other hand, Kang et al., (2014) tested 28 concrete beams of both high strength (54 MPa) and normal strength (27 MPa) concretes and found that the increased percentage of RA in concrete caused a reduction in displacement ductility and flexural capacity. While Sato et al. (2007), showed that the deflections in RA based RC beams is higher than that made of ordinary concrete under the same water-cement ratio and moment conditions. Moreover, beams made of recycled aggregate concretes showed wider cracks than concrete beams made of natural aggregates concrete but no significant difference in crack spacing was observed. In addition, Arezoumandi et al. (2015) replaced 100% NA with

2. The shear behaviour exhibits the strength against the type of structural failure when the beam fails due to a load that tends to produce a sliding failure on its materials along a plane that is parallel to the direction of the force.

3. In a one way RC beam, the reinforcement bars spanning along the long direction is referred to as transverse reinforcement.

4. Flexural strength is one measure of tensile strength of concretes. It is a measure of beam to resist failure in bending.

recycled aggregates in order to compare its flexural strength with concrete beams made of natural aggregates concrete. Interestingly, the cracks in the RA based RC beams spaced closer and the cracking moment was found to be 7% lower than concrete beams made of natural aggregates concrete. It is also noted that RA based RC beams had higher ultimate deflection and required level of flexural capacity compared to concrete beams made of natural aggregates concrete.

While a considerable amount of research was conducted to establish the structural suitability of reinforced concrete beam made of concrete containing various amounts of recycled aggregates, very few studies were conducted to test the performance of recycled aggregate based concretes using various industrial by-products, e.g., fly ash, silica fume, slag, as partial replacement for cement. The current study considers the use of Western Australia's C&D waste and industrial by-products as the physio-chemical properties of these materials could vary with regions, states and countries.

NA occupies approximately 80–85% of the volume of concrete, which Western Australian councils are still using in their various infrastructures, such as footpaths, retaining walls, and roadside curbs. However, these councils generate a huge amount of C&D wastes, most of which are sent to landfills due to a resource boom in Western Australia. This C&D waste accounts for quite a significant portion (48%) of municipality solid waste in WA (Waste Authority 2016). This figure is expected to increase in the future. While C&D waste can potentially be applied in pavements and concretes for low end infrastructure applications (Leek and Huband 2010), there is in fact a need for finding other potential applications as only 22% of the total 1.5M tonnes of these C&D waste generated in Perth each year is recycled.

Thus, there is a need to conduct a thorough feasibility study, including technical and sustainability assessment, on the effectives of the use of C&D wastes as complete replacement of NA in RC beam. This will increase the application of C&D wastes and divert wastes from the landfill rapidly.

The use of C&D wastes as RA and industrial by-products in concrete beam mix could have significant bearing on the economic and environmental performance of these beams. The use of recycled materials and industrial by products appears to be environmentally benign, but at the same time it is important to make sure that they are cost competitive and socially viable while maintaining quality environmental performance.

Shaikh et al. (2019), Crossin (2012), Braga et al. (2017) and Kurda et al. (2018) recently conducted an economic and environmental analysis, but they were not able to establish a suggestion for achieving environmentally friendly concrete in a cost-competitive manner or to determine 'eco-efficient' RC beams. Prior to these studies, Pon and de la Fuente (2013) used a multi-criteria decision making model to assess social, economic and environmental implications of reinforced concrete columns in buildings in Spain. Similarly, Wang et al. (2017) assessed the life cycle sustainability assessment of the replacement of OPC with fly ash concrete in China. However, there exists limitations in these studies that need to be addressed to expand the body of knowledge in this area of green building design. Firstly, the indicators and their level of significance are region specific or relevant to Spanish and Chinese situations. Since these indicators vary with regions due to socio-economic, geographical and climatic variations (Biswas et al. 2017), further investigation is need as to what would be the environmental performance of concrete beam in Australia using local indicators. Secondly, no study to date had used an eco-efficiency assessment framework for finding the concrete mixes or other infrastructure elements offering the reduced level of environmental impacts in a cost competitive manner.

This paper fills these gaps by first investigating the environmental and economic implications of the structural behaviour of RC beams made of NA, RA, fly ash and silica fume using an eco-efficiency assessment framework. Secondly, the inter- and intra-generational equity of eco-efficient options were discerned as a part of the social assessment.

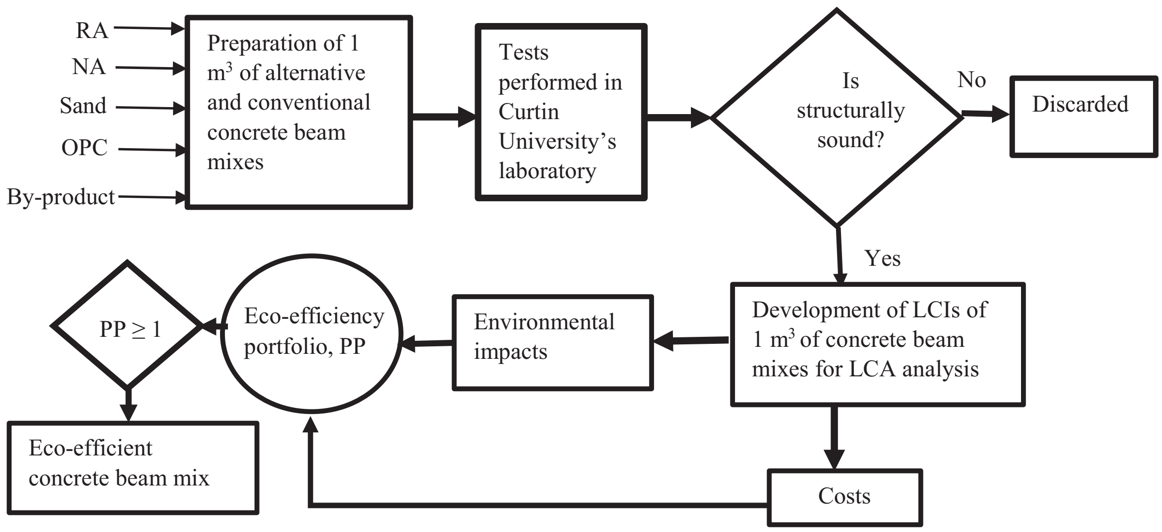
MATERIALS AND METHODS

This section discusses the procedure for conducting both technical and eco-efficiency performance of conventional and alternative concrete mixes to determine the applicability of recycled aggregate based concrete in RC beams, followed by a discussion of the social indicators used for assessing the social implications of eco-efficient concrete mixes.

Techno-eco-efficiency assessment framework

According to this framework, the structural performance of RC beams made of concrete mixes using both natural and recycled aggregates, OPC and by-product based cementitious materials was compared with the RC beam made of conventional concrete using natural aggregates and OPC. This helped ascertain whether the beams made of alternative concrete mixes could offer the same structural performance as conventional concrete made beams. Once the beams using alternative concrete mixes were found structurally suitable, their eco-efficiency performance was assessed. The first step of the eco-efficiency assessment is to develop a detailed life cycle inventory (LCI) of 1 m^3 of both alternative and conventional concrete mixes. LCI consists of the quantitative values of inputs used during mining to material production, transportation of materials to the construction site and concrete manufacturing stages of 1 m^3 of concrete mix. These inputs were used in the LCA analysis to estimate environmental impacts and costs associated with the manufacturing of 1 m^3 of concrete mix. These values were used to calculate the 'eco-efficiency portfolio (PP)' of these concrete mixes. If the eco-efficiency portfolio of the concrete mix is ≥ 1, the mix is regarded as eco-efficient.

FIGURE 1. Techno-eco-efficiency framework for assessing concrete beam mixes.



Experimental test for structural application

Compressive strength test: Six 100mm diameter cylinders were cast and tested to measure the compressive strength of each type of concrete. According to the Australian concrete standard (AS 3600:2018), three cylinders were used to measure the 28 days compressive strength. Another compressive strength test of cylinders of these concrete mixes was performed at the time when the RC beam was tested. The mixes with ≥40 MPa were considered suitable for use in structural members of the building, which were used to cast beams in this current investigation.

Structural testing of RC beams under flexure and shear: The structural testing regime consists of two series of beams.

Series 1: the beams were designed to fail in flexure under four point bending (Figure 2a).

Series 2: the beams were designed to fail in shear (Figure 2b).

For each series, four beams were cast of following mixes:

- M1C—Controlled concrete (100% cement and 100% natural aggregates),
- M2—100% recycled coarse aggregates and 100% cement.
- M3—50% recycled coarse aggregates, 50% natural aggregates, 90% cement and 10% micro silica and
- M4—50% recycled coarse aggregates, 50% natural aggregates, 60% cement, 30% fly ash and 10% micro silica.

Thus 8 beams for 2 series were cast and tested. Each beam was 1.5m long with a cross sectional area of 125×250 mm and contained both tensile and compression reinforcement as well as share reinforcements (Figure 2).

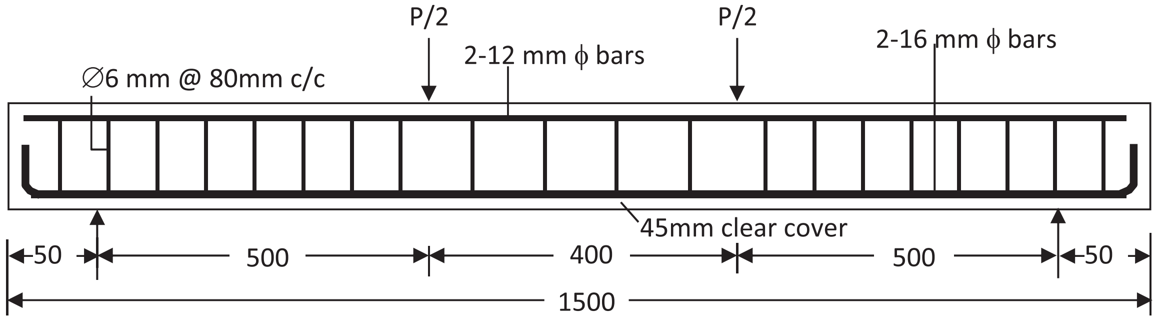
Figure 3 shows the test set-up and instrumentation of the RC beams. Two point loads were applied at the mid span of each beam. Two LVDTs (linear variable differential transducer) were placed on top of the supports to measure and monitor the deflection, while one LVDT was placed on top of the beam (or in the middle of 2 loads) to measure the mid-span deflection of the beam. Two electrical strain gauges were also attached to the top and bottom of each beam to measure the strain due to deformation during loading.

Eco-efficiency framework

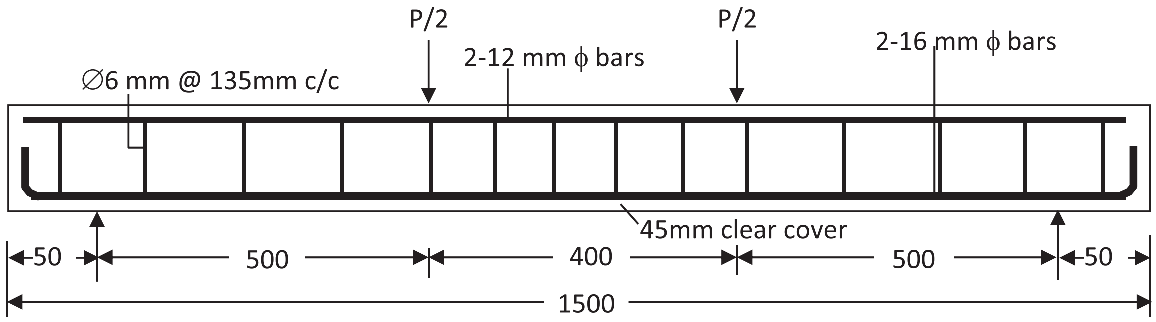
Once the beams made of M1C, M2, M3 and M4 were found structurally suitable for use, the eco-efficiency framework based on Kicherer et al. (2007) and Arceo et al. (2018) was developed to compare the eco-efficiency performance of these beams. The environmental impacts and costs of concrete beam mixes were first estimated to assess the eco-efficiency performance of these mixes. The objective of eco-efficiency is to produce a product or to deliver a service with reduced environmental impacts and costs. Sometimes the strategies for improving environmental impacts would increase the costs or vice versa. Therefore, an eco-efficiency framework was used to address this issue through a comparative assessment process to identify the concrete mix that delivers better environmental performance in a cost-competitive manner.

Since the eco-efficiency framework assessed the environmental and economic performance, a separate assessment for assessing social implications was conducted to assess the overall

FIGURE 2. Reinforcement details and schematic of load setup.



(a) Reinforcement details of beam designs to fail in flexure



(b) Reinforcement details of beam designs to fail in share

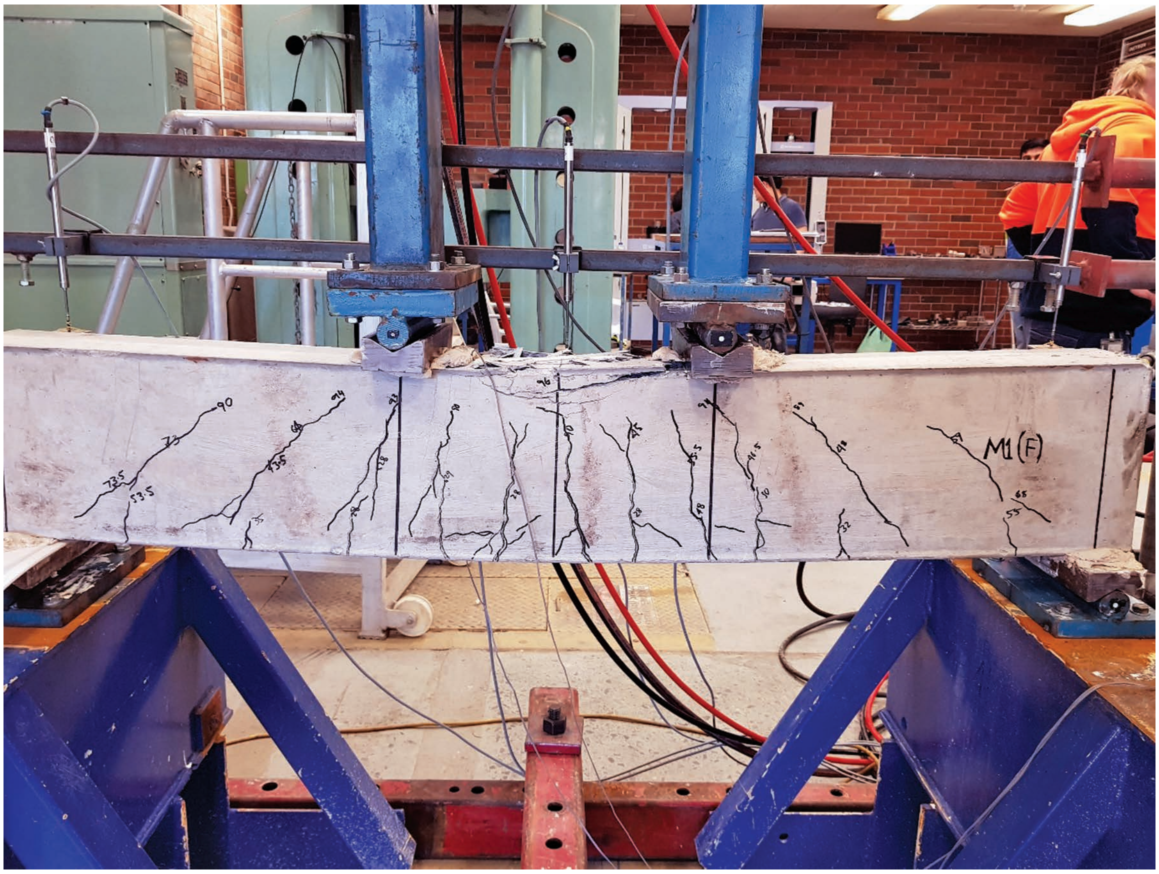
sustainability implications of the replacement of natural aggregates and cement with recycled aggregates and industrial by-products. Inter-generational and intra-generational equity indicators were chosen as the social indicators to assess the conservation of energy and land for future generations (inter-generational) and job creation for the current generation (intra-generational) as measures of social equity.

The first step in the Eco-efficiency Assessment (EEA) framework is to carry out a life cycle assessment to calculate the life cycle environmental impacts of concrete mixes. The next step calculates the costs of concrete beam mixes.

Step 1—Determination of environmental impacts: Fourteen environmental impacts that are relevant for environmental assessment of Australia's building and construction sector as listed below were calculated. The impacts that are listed here are based on a local situation and were obtained from the Building Product Innovation Council (Bengtsson and Howard 2010a):

Global warming (kg CO_2 eq per inhabitant per year)
Abiotic resource depletion (kg Sb eq per inhabitant per year)
Land use and ecological diversity (ha. a per inhabitant per year)
Water depletion (m^3 H_2O per inhabitant per year)
Eutrophication (kg PO_4 eq per inhabitant per year)

FIGURE 3. Test set-up and instrumentation of the reinforced concrete (RC) beams.



Acidification (kg SO_2 eq per inhabitant per year)
Fresh water aquatic ecotoxicity (kg 1,4-DB eq per inhabitant per year)
Marine aquatic ecotoxicity (kg 1,4-DB eq per inhabitant per year)
Terrestrial ecotoxicity (kg 1,4-DB eq per inhabitant per year)
Photochemical smog (kg NMVOC per inhabitant per year)
Ozone depletion kg CFC-11 eq per inhabitant per year
Ionising radiation kBq U235 eq per inhabitant per year
Human toxicity kg 1,4-DB eq per inhabitant per year
Respiratory inorganics kg PM2.5 eq per inhabitant per year

These environmental impacts of the concrete mixtures were calculated following ISO14040-44 guidelines (ISO 2006). These guidelines consist of goal and scope, life cycle inventory (LCI), environmental impact assessment and interpretation. The goal of the LCA is to determine the environmental impacts associated with the use of C&D wastes and by-products in concrete beam mixes. This LCA applies a 'cradle to gate' approach, including the mining of raw materials, the production of the construction materials, transportation of these materials for concrete beam manufacturing, and manufacturing stages. The concrete beam mixes of 1 m^3 was chosen as the functional unit in this LCA study in order to carry out a mass balance to estimate the energy and materials used to produce 1 m^3 of concrete beam for the four different mixes (Table 1).

Developing an LCI is essential for estimating 14 environmental impacts. The energy consumed in manufacturing the concrete was sourced from Biswas et al. (2017). Table 1 shows the LCIs consisting of inputs, including cement, FA, SF, natural and virgin aggregates, sand, superplasticiser, water, electricity and transportation, for the four concrete beam mixes, based on the aforementioned experiment conducted for structural performance testing. Since the same amount of steel is used in all beam mixes for reinforcement purposes, this has been excluded in the assessment for this comparative analysis.

The inputs of life-cycle inventory in Table 1 were incorporated into SimaPro 8.4 LCA software (Pré Consultants 2018) in order to link them to relevant emission factor databases. The emission databases for most of the inputs were based on local conditions of Western Australia. Firstly, the inputs of each concrete beam mix were multiplied by the corresponding emission factors to determine 14 environmental impacts of each input and then the impacts of all inputs were added to ascertain the total life cycle environmental impacts of each mix. In the absence of Western Australian emission factor databases, new databases were created using available local

TABLE 1. Life cycle inventory of concrete mixtures.

Inputs/ Constituents	Concrete mixes				Sources of materials
	M1C	M2	M3	M4	
Ordinary Portland Cement (OPC)	449	449	402	268	Cockburm Swan Munster
Fly ash	447	447	402	268	Gladstone/ Eraring
Silica fume				134	Xypex, Bibra Lakes WA
Water			45	45	
NA 20mm	179	179	179	179	Holsim gosnells
NA 10mm	790		395	395	holsim gosnells
RA 10mm	395		197.5	197.5	All Earth Group and Capital Recycling
RA 1**nputs/** 0mm		790	395	395	All Earth Group and Capital Recycling
Sand		395	197.5	197.5	Hanson, Lexia
Super-plasticizer (mL)	592	592	592	592	bass rheo build 1000nt
Total weight (kg)	2403	2428	2478	2453	
Total weight excl. water (kg)	2,224	2,249	2,299	2,274	
Transportation—tkm road	52	39	50	49	
Transportation—tkm sea	0	0	0	383	
Manufacturing	75	76	77	77	

raw data from industries/processes. Australian emission databases were considered for cement, silica fume, recycled aggregates, fly ash, sand, electricity, transportation and water (Life Cycle Strategies Pty Ltd. 2015). The unit of transportation was considered as tonne-kilometres or tkm in order to determine the emissions associated with transportation. Since databases for coarse aggregate in WA were not available during the time of the studies, new databases for these construction materials were created in the software by using the information on the amount of diesel consumption for crushing the aggregate (i.e., 0.052 Mega Joule per kg of 10mm coarse aggregate crushed) (Shaikh et al. 2019). Australian emission databases for the combustion of diesel for crushing aggregates and the electricity generation from the Western Australian South Western Integrated System were used. The foreign database (i.e., Eco-invent) was used for calculating the emissions for the production of the plasticiser.

In Australia, only a few environmental impacts can be estimated due to lack of a relevant impact assessment method applicable for the region. Since this study requires the estimation of 14 environmental impacts, these were calculated using a number of relevant methods available in SimaPro 8.4, as suggested appropriate for Australia by Bengtsson and Howard (2010a) and Renouf et al. (2015). The impact assessment methods used to calculate the impacts are shown in Table 2. The input values in the LCI of each concrete beam mix were multiplied by the corresponding emission factors to estimate the environmental impacts.

TABLE 2. Impact assessment methods to estimate the environmental impacts.

Impact Assessment Method	Environmental Impact	Unit
IPCC GWP 100 (IPCC, 2013)	Global warming	t CO_2 eq
Australian indicator set v2.01	Eutrophication	kg PO_4^{3-} eq
	Water depletion	m^3 H_2O
	Land use and ecological diversity	Ha a
ReCiPe 2008 (Goedkoop et al., 2013)	Human toxicity	kg 1,4-DB eq
	Terrestrial ecotoxicity	kg 1,4-DB eq
	Freshwater ecotoxicity	kg 1,4-DB eq
	Marine ecotoxicity	kg 1,4-DB eq
CML 2 baseline 2001 (Guinee, 2001)	Abiotic depletion	kg Sb eq
ReCiPe Midpoint (E) V1.12 / Europe Recipe E (Goedkoop et al., 2013)	Ozone depletion	kg CFC-11 eq
	Acidification	kg SO_2 eq
	Photochemical smog	kg NMVOC
	Ionising radiation	kg U235 eq
TRACI v2.1 (Bare et al., 2012)	Respiratory inorganics	kg $PM_{2.5}$ eq

eq—equivalent, CO_2—carbon dioxide, PO_4^{3-}—phosphate, Ha. a—hectare years, NMVOC—non-methane volatile organic compounds, U235—uranium 235, Sb—antimony, CFC—choloroflurocarbon, SO_2—sulphur dioxide, PM—particulate matter

Since the emission factors of construction materials used in this study were based on the mix of both local and foreign databases, there may be an accuracy issue with these LCA outputs. In order to estimate these uncertainties or level of accuracies, Monte Carlo Simulation (MCS) was carried out to determine the uncertainty of each of these data points and predict the effect that a variable would have on LCA outputs for concrete beam mixes (Clavreul 2012). The simulation involves an iterative process utilising an input value from a probability distribution at 95% confidence level to produce a distribution of all possible values for 1,000 iterations (Goedkoop 2013).

Step 2—Cost calculation: Using the same LCI of LCA in Table 1, an economic analysis was carried out to determine the unit cost for the four concrete mixes. The same functional unit that was used for life cycle assessment of RC beams was considered in the economic analysis (i.e., USD/m^3) to maintain the consistency of economic and environmental assessments.

The cost of labour that was excluded in the life cycle inventory was included using a local wage rate to determine the overall cost. Most of the prices of different concrete constituents were obtained from Mick Ellis, Senior Technical Officer of the Curtin Civil Engineering Laboratory:

- Ordinary Portland Cement (OPC) $7.06/20kg bag, $395.36/pallet (56 bags) delivered in 2018
- Silica fume $6.50/10kg bag, $546/pallet (84 bags) delivered in 2014
- Natural aggregates (NA) 20mm $54.75/tonne, $810.03/13.45T delivered in 2016
- NA 10mm $55.47/tonne, $721.11/13T delivered in 2012
- Sand $36.72/tonne, $527.12/13.05T delivered in 2016

The prices for the following by-products and waste materials were obtained from the National Ash Manager of Cement Australia and Capital Recycling in Perth:

- Recycled aggregates (RA) 10mm $15/tonne
- RA 10mm $18/tonne
- Fly ash $120/tonne

The price of the super-plasticizer chemical was found online (AUD10/litre). The electricity price was obtained from WA's local electricity provider (Synergy, 2018). Since both road and sea transport was used to procure the materials, the cost of this transport (i.e., 0.09/tkm for truck and 0.03 for shipping) was sourced from the Department of Infrastructural and Regional Development (DIRD 2017).

The price was inflated using relevant year inflation rates when inputs were purchased before 2018. Once the prices of all inputs/constituents were finalised, an economic analysis was conducted to calculate the unit costs of RC beams. Their unit costs were added to the profit margin to determine the price of the mixes. Following Homeone (2018), a profit margin of 20% was utilized.

Step 3—Normalisation of environmental impacts: The environmental impacts are normalised and weighted (using environmental impact weighting factors) to derive a single score for overall environmental performance of each of RC beam, while the cost of beams is normalised to the recent Australian Gross Domestic Product (GDP). The normalised cost and environmental impact values of concrete beam mixes are then used to generate the 'eco-efficiency portfolio'. The following steps are followed to conduct an eco-efficiency portfolio analysis.

Normalisation and weighting of environmental impacts: For the concrete beam mixes, the normalised values (NV_i) of each environmental impact "i" is the ratio between each life cycle environmental impact ($LCEI_i$) and the gross domestic environmental impact ($GDEI_i$) in Table 3 (Eq. 1) (Kicherer et al., 2007).

$$NE_i = \frac{LCEI_i}{GDEI_i} \, [\text{inhabitants}] \quad (1)$$

The calculated life cycle environmental impacts were divided by the latest Australian normalisation factors to estimate the normalised values. The individual normalisation factors represent the respective unit of each environmental impact per Australian inhabitant per year. This represents the equivalent amount of environmental impact a single person releases every year (Table 3).

These normalised values were aggregated into a single environmental score using the relative weighting factor (WF) of each impact in Australia. These WFs were obtained from Howard et al. (2010b) (Table 3). The normalised environmental impacts (EI) were estimated using Eq. 2 (Arceo et al., 2018).

TABLE 3. Normalisation factors of the environmental impacts.

Environmental Impact	Gross Domestic Environmental Impact (per inhabitant/y)	Weights
Global warming potential	28,690 t CO_2 eq	19.50%
Eutrophication	19 kg PO_4^{3-} eq	2.90%
Water depletion	930 m^3 H_2O	6.20%
Land use and ecological diversity	26 Ha a	20.90%
Photochemical smog	75 kg NMVOC	2.80%
Human toxicity	3,216 kg 1,4-DB eq	2.70%
Terrestrial ecotoxicity	88 kg 1,4-DB eq	10.30%
Freshwater ecotoxicity	172 kg 1,4-DB eq	6.90%
Marine ecotoxicity	12,117,106 kg 1,4-DB eq	7.70%
Ionising radiation	1,306 kg U235 eq	1.90%
Abiotic depletion	300 kg Sb eq	8.20%
Ozone depletion	0.002 kg CFC-11 eq	3.90%
Acidification	123 kg SO_2 eq	3.10%
Respiratory inorganics	45 kg $PM_{2.5}$ eq	3.00%

$$EI = \sum_{i=1}^{14} NE_i \times WF_i \ [\text{inhabitants}] \tag{2}$$

Normalisation of costs: The LCC_{total} of concrete beam mixes were normalised using the recent Australian gross domestic product (GDP). The values of GDP (AUD1,815,372 million) and the total population (25.2 million), obtained from ABS (2018) and ABS (2019), were used to determine the GDP per inhabitant.

This normalised cost (NC) is expressed as the number of Australian inhabitants generating the same amount of annual GDP (Eq. 3) (Arceo et al., 2018).

$$NC = \frac{LCC_{total}}{GDP} \ [\text{inhabitants}] \tag{3}$$

Step 4—Generation of eco-efficiency portfolio: The initial positions (PP_e and PP_c) of the concrete beam mixes "n" were calculated as the ratio of the normalised cost/environmental impact values and the average normalised cost/impact values of concrete beam mixes "j" (Eqs. 4 and 5) (Arceo et al., 2018).

$$PP_{e,n} = \frac{EI_n}{(EI)/j} \tag{4}$$

$$PP_{c,n} = \frac{NC_n}{(NC)/j} \tag{5}$$

These portfolio positions calculated were adjusted using the environment to cost relevance factor ($R_{e,c}$) (Eq. 6) in order to determine whether cost is more effective ($R_{e,c} < 1$) for determining eco-efficient RC beams or vice-versa. This shows how the changes in the environmental and economic performance of one concreate beam mix could potentially affect the same performance of another mix.

$$R_{e,c} = \frac{\left(\sum EI\right)/j}{\left(\sum NC\right)/j} \tag{6}$$

This relevance factor was used to determine the final portfolio positions of concrete beam mixes (PP'_e and PP'_c) in which the environmental impact and cost values were balanced equally (Eqs. 6 to 8) (Arceo et al., 2018).

$$PP'_{e,n} = \left[\left(\sum PP_{e,n}\right)/j + \left[PP_{e,n} - \left(\left(\sum PP_{e,n}\right)/j\right)\right] \cdot \sqrt{R_{e,c}}\,\right] / \left[\left(\sum PP_{e,n}\right)/j\right] \tag{7}$$

$$PP'_{c,n} = \left[\left(\sum PP_{c,n}\right)/j + \left[PP_{c,n} - \left(\left(\sum PP_{c,n}\right)/\ j\right)\right] / \sqrt{R_{e,c}}\,\right] / \left[\left(\sum PP_{c,n}\right)/j\right] \tag{8}$$

If the ratio of $PP'_{e,n}$ and $PP'_{c,n}$ is ≥ 1, then the option is eco-efficient. It means that the portfolio position will be either on the diagonal line or above the line of a rectangular portfolio plot.

Social implications

Once the eco-efficient concrete beam mixes have been ascertained, the social implications of these mixes were assessed. The social benefits of the concrete beam mixes depend on the amount of utilised waste or by-product used in these mixes to conserve natural resources and to divert wastes from landfills. The amount of C&D waste that was diverted from landfills due to their use in concrete mixes was used to estimate the market for recycled aggregates for job creation. The empowerment through job creation enhances intra-generational equity, which is one of the key principles of sustainable development. The reduction in landfill area and the associated conservation in natural resources (i.e., reduction of land use and deforestation due to avoidance of acquiring virgin materials), resulting from the utilisation of the C&D wastes and industrial by-products was then used to determine the intergenerational equity benefits that arise from the resource conservation, avoided land use of virgin aggregates quarries and the waste diverted from the landfill. The following indicators were deemed relevant for assessing the social implications of concrete beam mixes (Biswas and Cooling, 2013).

Employment Opportunity is one of the key indicators for intra-generational social equity. It measures the potential job creation for recyclers due to conversion of construction and demolition wastes and by-products to concrete beam mixes.

Intergenerational Social Equity—It measures the conservation of energy and land for the future generations due to the use of recycled aggregates in RC beams. The substitution of a tonne of virgin resource with a tonne of wastes/by-product could also conserve precious fossil resources for the future generations. Secondly, the land areas conserved in both landfill and quarry sites were added to determine the amount of land use avoided due to the replacement of virgin natural aggregate with recycled aggregates.

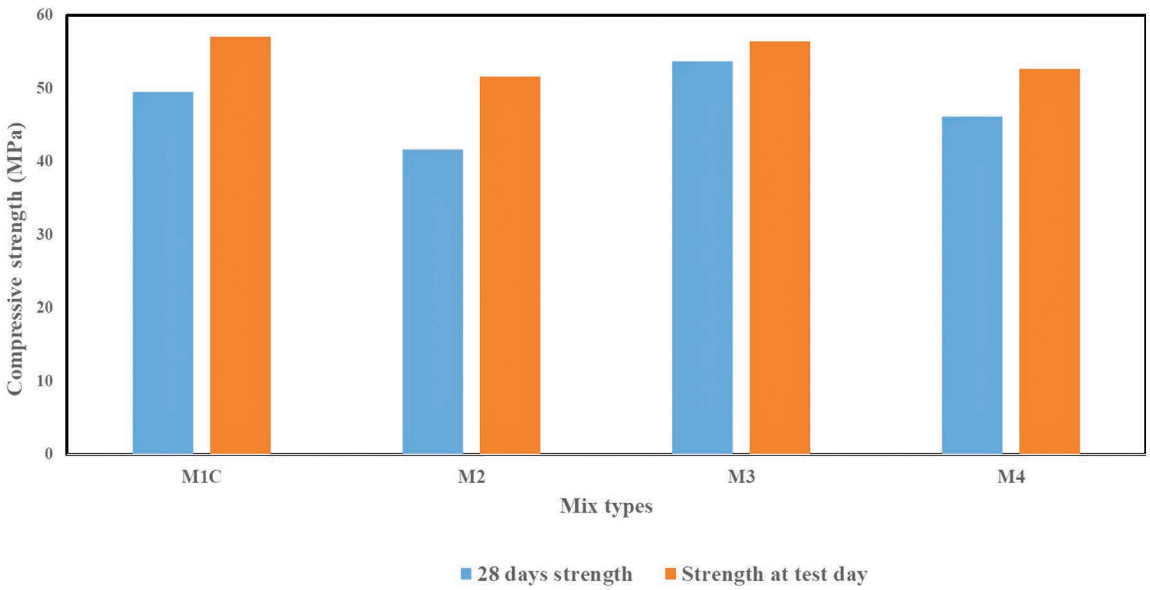
RESULTS AND DISCUSSION

Technical feasibility assessment

A technical feasibility assessment of concrete beam mixes is a must prior to considering its triple bottom line sustainability benefits. As a result, key structural performance tests including compressive strength of concretes and flexural and shear behaviour of beams were conducted to assess their structural suitability.

Compressive strength test: Figure 4 shows the measured compressive strength of all four concrete beam mixes. M2 concrete using 100% RA shows about 15% reduction in 28 days compressive strength compared to M1C concrete containing 100% natural aggregates (NA). When 50% NA is replaced by RA and 10% OPC is replaced by silica fume (SF) in M3, the 28 days compressive strength of concrete is increased by about 10% compared to M2. When 30% fly ash (FA) is used as a partial replacement of OPC in M3 to form M4 concrete, about 15% reduction in 28 days compressive strength is noticed compared to M3 containing 90% OPC and 10%SF and also a 6% reduction compared to M1C. Similar trends in variation in measured compressive strength during test days are also observed in all four types of concretes (Figure 4). Whilst RA based concretes appear to demonstrate comparable good performance as M1C, they at least meet the compressive strength requirement of structural members of buildings.

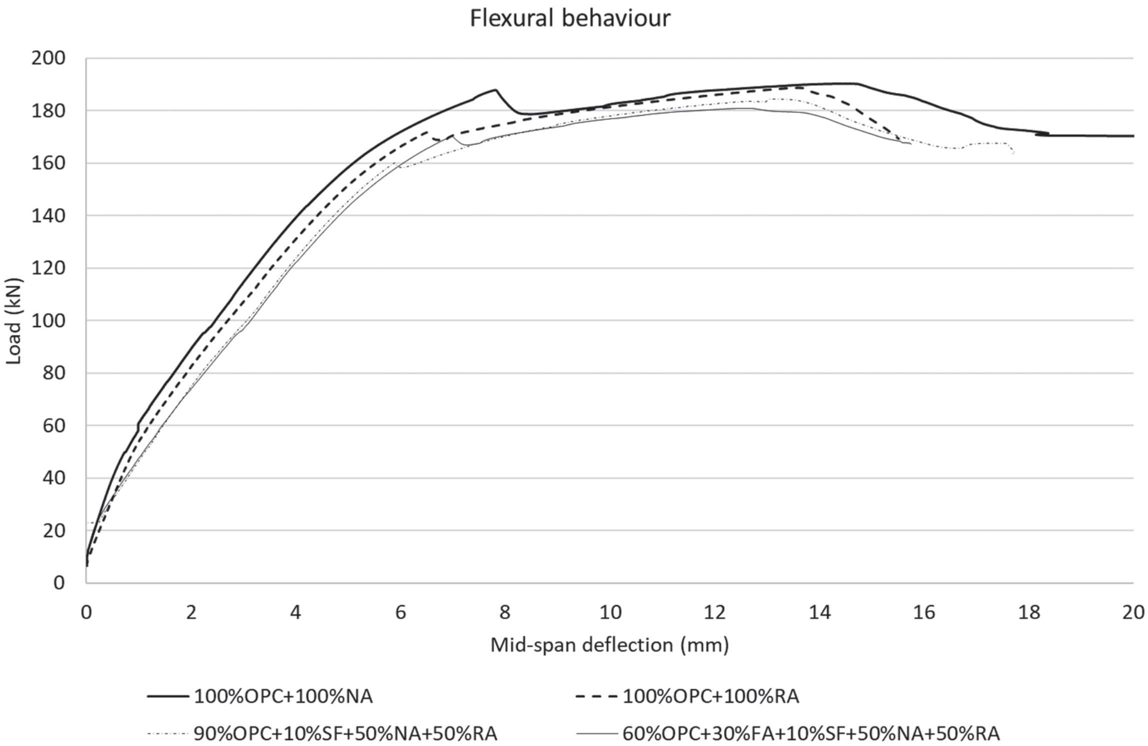
FIGURE 4. Compressive strength of four types of concretes measured at 28 days and at test dates.



Structural behaviour of RC beams under flexure and shear: The load vs. mid-span deflection behaviour of RC beams subjected to four-point bending is shown in Figure 5. Figure 5 confirms that all four RC beams demonstrated similar load mid-span deflection behaviour. The first crack happened in all beams between 30 and 40kN loads, after which a change in stiffness of the beams happened. Until yielding of steel, the RC beam made of M1C concrete mix shows slightly higher stiffness than M2, M3 and M4 RC mixes. After yielding, the increase in deflection with load can be seen in all four RC beams. The RC beam made of M1C yielded at about 186kN load, whereas the RC beam made of M2 RC beam (100%OPC+100%RA) yielded at about 171kN load. The RC beam made of M3 (90%OPC+10%SF+50%NA+50%RA) exhibited yield load of about 160kN, whereas the RC beam made of M4 (60%OPC+30%FA+10 %SF+50%NA+50%RA) exhibited yield load of about 169kN. Nevertheless, the variation of yield load among the four types of beams is within 15% which is considered reasonable. On the other hand, the variation of ultimate load among the four beams are even lower than yield load by about 6%. This clearly shows that variation in compressive strength of concretes due to the use of different amounts of RA, fly ash and silica fume does not significantly affect the ultimate load capacity of RC beams under flexure. The cracking pattern under flexure in all four beams is shown in Figure 6 also agrees well with this observation, where almost the same number of cracks can be seen in all beams.

Under shear a different behaviour in all four beams is observed. Figure 7 confirms that the ultimate failure load in shear of the RC beam made of M2 concrete mix is about 4% higher than that of M1C. The RC beam made of M3 (90%OPC+10%SF+50%NA+50%RA) concrete exhibited about 6% higher ultimate load than the control concrete (i.e., M1C) under shear. However, about 25% reduction in ultimate load capacity of the RC beam was observed when it is made of M4 concrete mix (i.e., 60%OPC+30%FA+10%SF+50%NA+50%RA). Despite significant variation in the ultimate load of RC beams made by concretes containing RA, the

FIGURE 5. Load mid-span deflection behaviour of reinforced concrete (RC) beams made by various types of concretes under flexure.



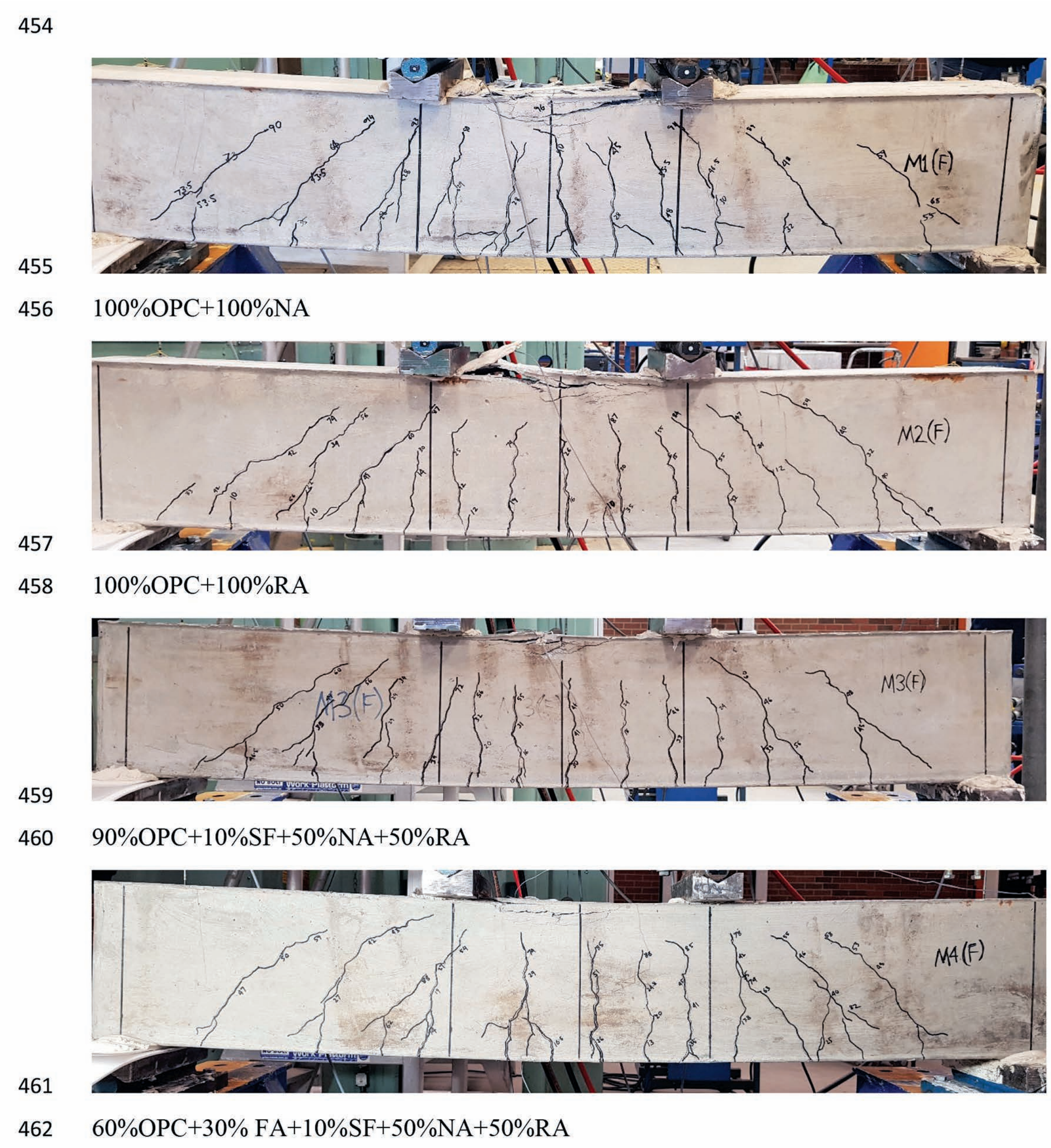
cracking patterns under shear failure of these beams are very similar to that of the control concrete beam as shown in Figure 8.

Thus, through these experiments, it was found that the failure behaviour in terms of the cracking pattern of recycled aggregates concrete beams is very similar to that of the control concrete beam under flexure. Also, these beams show very similar cracking behaviour under shear compared to the control concrete beam. Thus, these RC beams can potentially be considered for building construction.

Environmental and economic performance of concrete beam mixes

The overall normalised environmental impacts of M1C, M2, M3 and M4 concrete beam mixes have equivalent environmental impacts of 5.50×10^{-3}, 5.59×10^{-3}, 5.10×10^{-3} and 3.97×10^{-3} inhabitants per year (Fig. 9). Global warming potential was found to be the dominant environmental impact (i.e., 64–65%), followed by some other major environmental impacts, including photochemical oxidation (13%), terrestrial acidification (9%) eutrophication (7%) and water use (2–3%). The remaining impacts account for only 4 to 5% of the total normalized environmental impacts. However, these impacts vary with regions. Biswas et al. (2017) found for Qatari concrete that radioactive waste disposal had the highest impact, followed by GWP, abiotic depletion potential-element (ADPE), acidification potential, net use of fresh water and other impacts. Although dominant impacts are common in previous and current studies, there are some variations in terms of severity. In the case of these eco-points, the highest impact does not necessarily depend on the type of inputs used, but also depends on the weights that are

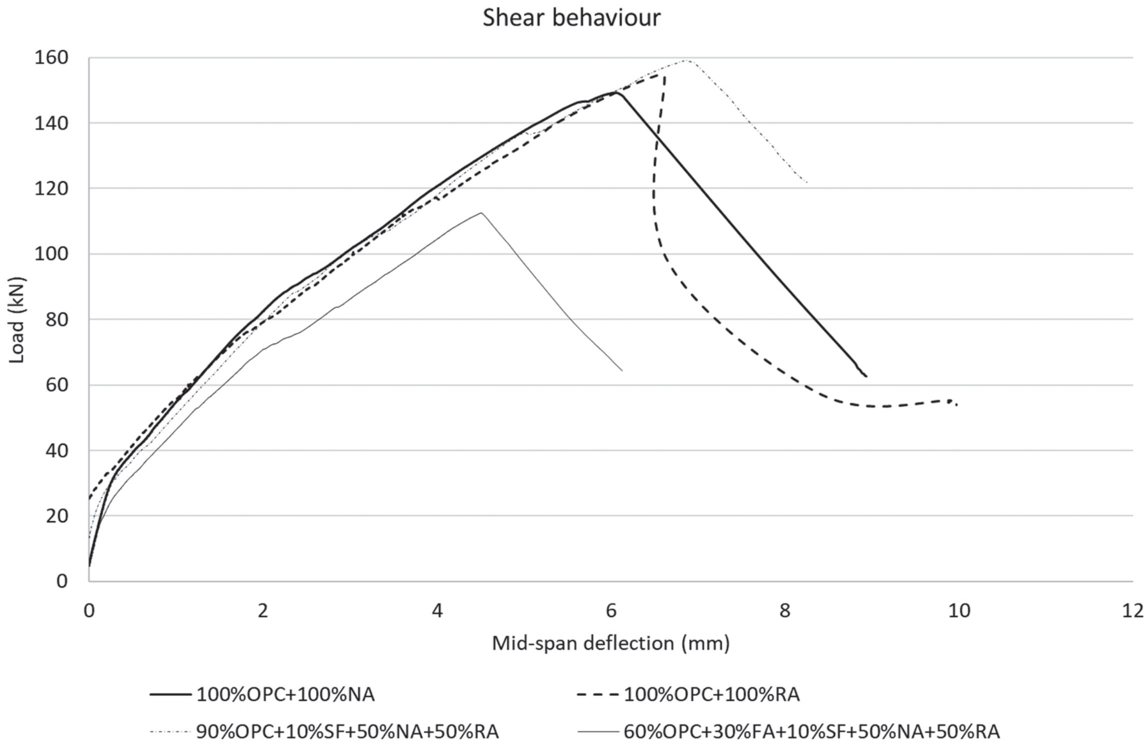
FIGURE 6. Cracking and failure behaviour of RC means made by various types of concretes under flexure.



allocated to impacts in different countries on the basis of monetisation and also their links to scientific and policy targets, (i.e., costs associated with minimising impact) and expert panel weighting (i.e., simply asking local experts for their opinion on what is more important) (Pre Consultants, 2016). GWI value is very high for Australian concrete due to the per capita GHG emission of Australia being the highest in the world and also more than 80% of electricity is generated from fossil fuel power plants (Australian Government2020).

The MCS was conducted to present the accuracy of results as the emission factors used in this LCA are not completely local due to information gaps and that some input data were

FIGURE 7. Load mid-span deflection behaviour of reinforced concrete (RC) beams made by various types of concretes under shear



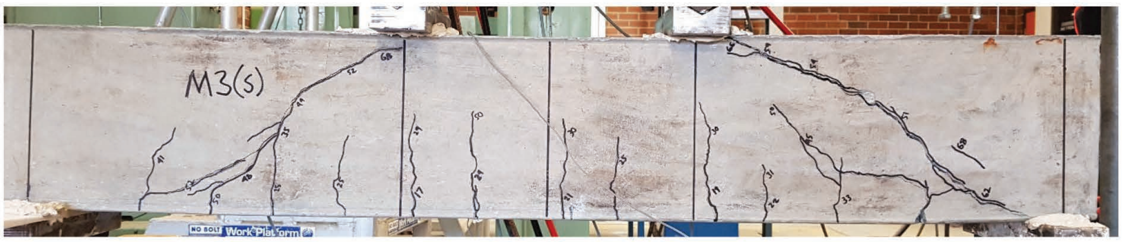
sourced from the literature and consequently not measured during the experiment. The coefficient of variation (CV) of GWI, eutrophication, water use, acidification, photo-oxidant and respiratory effect vary between 2% and 8% inferring that the degree of uncertainty in the calculated values of these impacts is relatively small (Table 4). These environmental impacts have lower CVs due their being directly related to the mining and manufacturing of products and are not directly affected by land use changes, variation in topography, demography, water bodies and vegetation coverage. However, discrepancies were observed for more regional and local impact categories (i.e., land use, human toxicity—carcinogenic fresh water aquatic eco-toxicity, marine aquatic eco-toxicity, ozone depletion, abiotic depletion) due to the above reasons (Yoshida et al., 2013). Therefore, these environmental impacts are deemed to be relatively less important for the housing industry (Islam et al. 2015)

The mining to material stage accounts for a significant portion of total global warming impacts for both controlled and recycled concrete aggregates. This stage accounts for 78% of GWI even with 40% substitution in cement with by-products in concrete and 100% use of recycled aggregates (Table 5). Figure 10 confirms that ordinary Portland cement (OPC) accounts for significant portions of the total emissions for both conventional and by-product based concrete beam mixes and is considered as the main cause for increasing the overall GWI. Although both M1C and M2 mixes use 100% OPC, the latter produces more GHG than the former. This is because the recycled aggregate that is 100% used by the M2 mix has a higher emission factor (0.00563 kg CO_2e-/kg) than that of the natural aggregates (0.00477 kg CO_2e-/kg) used by the M1C mix. A large amount of energy is consumed to demolish buildings and

FIGURE 8. Cracking and failure behaviour of RC means made by various types of concretes under shear.

100%OPC+100%NA

100%OPC+100%RA



90%OPC+10%SF+50%NA+50%RA

60%OPC+30% FA+10%SF+50%NA+50%RA

FIGURE 9. Environmental impacts of 4 concrete beam mixes.

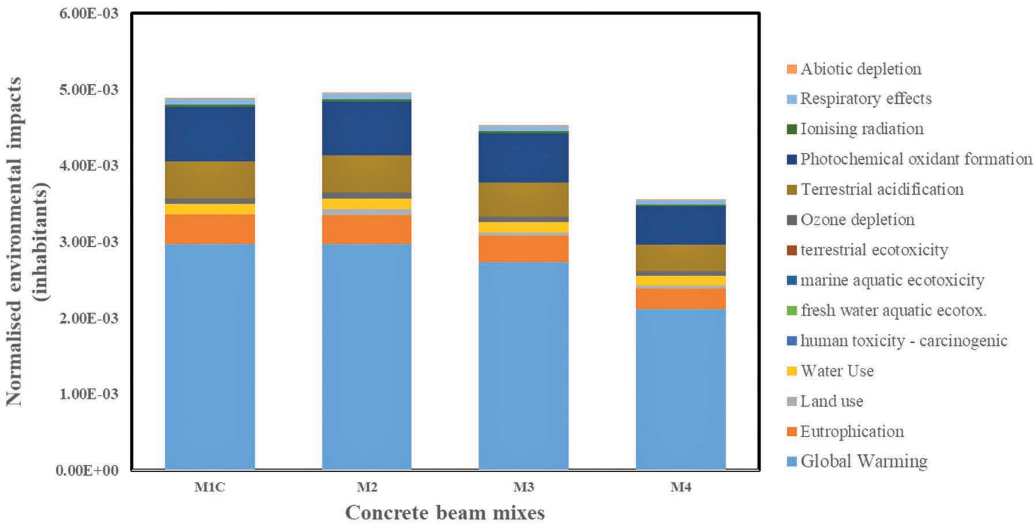


TABLE 4. MCS of LCA outputs for 4 concrete mixes.

		Mean values of impacts			
Impact category	**Units**	**M1C**	**M2**	**M3**	**M4**
Global Warming	kg CO_2-eq	437 (2.04%)	437.0 (2.11%)	402.0 (2.13%)	312 (1.98%)
Eutrophication	kg PO_4-eq	2.51E-01 (6.9%)	2.5E-01 (4.97%)	2.3E-01 (5.4%)	2.E-01 (4.25%)
Land use	Ha a	9.21E-04 (47.74%)	9.3E-03 (5.15%)	5.0E-03 (10.31	5.E-03 (6.27%)
Water Use	m^3 H_2O	2.02 (2.74%)	2.1 (2.62%)	2.0 (2.5%)	2 (2.07)
Human toxicity	DALY	1.14E-06 (54.15%)	1.1E-06 (43.49%)	1.1E-06 (50%)	8.E-07 (42.8%)
Fresh water aquatic ecotoxicity	Day	9.63E-11 (38.97%)	1.0E-10 (37.95%)	9.1E-11 (37.3%)	7.E-11 (33.1%)
marine aquatic ecotoxicity	Day	4.78E-08 (52.2%)	4.7E-08 (475)	4.6E-08 (47.15%)	4.E-08 (44.25%)
terrestrial ecotoxicity	Day	2.03E-11 (12.46%)	2.0E-11 (13.56%)	1.9E-11 13.26%)	2.E-11 (12.39%)
Ozone depletion	kg CFC-11 eq	3.55E-06 (33.39%)	3.9E-06 (32.98%)	3.5E-06 (.80%)	3.E-06 (31.57%)
Terrestrial acidification	kg SO_2 eq	1.94 (2.44%)	1.9 (2.55%)	1.8E (2.37%)	1 (2.34%)
Photochemical oxidant formation	kg NMV-OC	1.90 (2.41%)	1.9 (2.44%)	1.7 (2.27%)	1 (2.32%)
Ionising radiation	kBq U235 eq	2.29 (13.%)	2.2 (14.3%)	2.1 (13.3%)	2 (14.015)
Respiratory effects	kg PM2.5 eq	1.11E-01 (7.79%)	1.2E-01 (8.16%)	1.0E-01 (7.57%)	8.E-02 (7.65%)
Abiotic depletion	kg Sb eq	1.45E-04 (32.68%)	1.6E-04 (35.05%)	1.4E-04 (31.635)	1.E-04 (30.78%)

Note: the percentage values within bracket are the co-efficient of variance (CV)

TABLE 5. Breakdown of global warming impacts (kg CO_2 e-) in terms of stages

Specifications	Mining to materials	Transportation	Construction	Total
M1C	380.2 (87%)	4.4 (1%)	52.4(12%)	437
M2	380.2 (87%)	4.4 (1%)	52.4 (12%)	437
M3	342 (85%)	4 (1%)	56 (14%)	402
M4	250 (80%)	6 (2%)	56 (18%)	312

then to crush this demolished waste to produce recycled aggregates, which might have resulted in the increase of GHG emissions.

In the current analysis, the results of LCA in terms of 1 m^3 concrete (i.e., between 312–437 kg CO_2 e) are comparable to a similar Australian LCA of 1 m^3 of Australian concrete mix (401kg CO_2 e-) by Crossin (2012).

Table 6 shows that the price of 1 m^3 equivalent of control (M1C) and alternative concrete mixes, M2, M3, and M4 are $351, $311, $350 and $325, respectively. The savings associated with the replacement of conventional concrete with M2, M3, and M4 concrete beam mixes are 11%, 0.4% and 7%, respectively. Interestingly, as with environmental savings, M4 had lower costs than M3 and controlled (M1C) mixes. The replacement of M1C with M3 improved the environmental performance without entailing an additional cost. The use of M2 can reduce the cost significantly due to the lower price of recycled aggregates, but it does not offer any environmental benefits. Thus, it is difficult to ascertain which mixes are actually eco-efficient. Accordingly, an eco-efficiency framework was applied to determine the eco-efficiency performance of concrete mixes by mitigating environmental impacts in a cost competitive manner. The next section presents an eco-efficiency analysis in order to determine the concrete beam mix offering environmental benefits in a cost competitive manner.

FIGURE 10. Breakdown of GWI of MIC (a) and M4 (b) concrete beam mixes in terms of inputs.

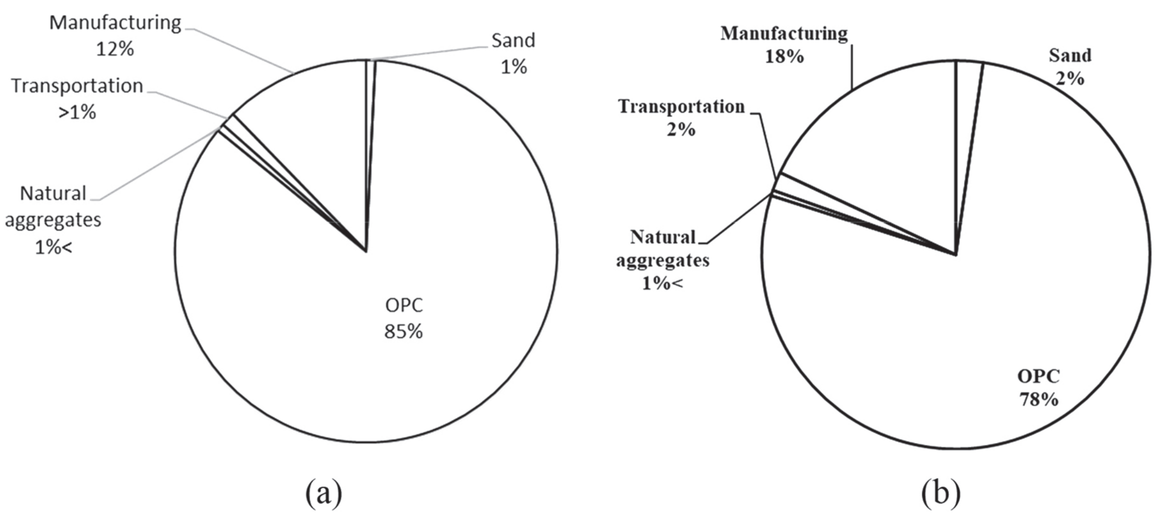


TABLE 6. Price of different concrete mixes ($\$/m^3$).

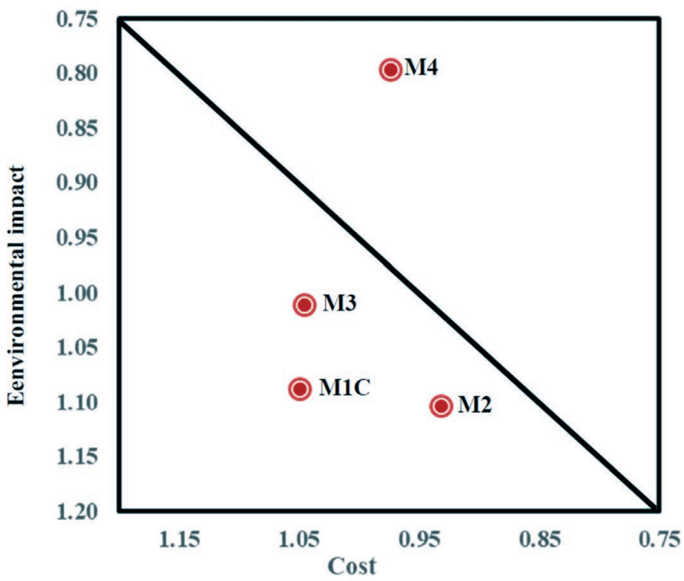
Constituents	M1C	M2	M3	M4
OPC	158	158	142	95
Class F Fly ash	0	0	0	16
Silica fume	0	0	29	29
Water	0	0	0	0
NA 20 mm	43	0	22	22
NA 10 mm	22	0	11	11
RA 20 mm	0	23	11	11
RA 10 mm	0	9	5	5
Sand	22	22	22	22
Super-plasticizer (mL)	0	0	1	1
Transportation—tkm road	5	4	4	4
Transportation—tkm sea	0	0	0	11
Manufacturing	41	42	43	42
Labour	2	2	2	2
Total cost	293	259	292	271
Profit margin	59	52	58	54
Price	351	311	350	325

Eco-efficiency analysis

The generation of an eco-efficiency portfolio was performed by following the eco-efficiency framework. This analysis mainly focused on the determination of the most eco-efficient concrete beam mix. The positions of the concrete beam mixes in the eco-efficiency portfolio were calculated using the environmental impact and costs values in equations 1 to 8. The options above the diagonal line are considered as eco-efficient options. The concrete beam mix using 50% recycled aggregates, 50% natural aggregates, 60% OPC and 40% cementitious by-products (i.e., fly ash and silica fume) were found to be the only eco-efficient concrete beam mix. Figure 11 shows that this option is located above the eco-efficiency line; it also has the greatest perpendicular distance from this line. Although the environmental performance of M3 is better than the controlled mix (M1C) by 8%, it was not found eco-efficient at the same cost as MIC. It means that either environmental performance of M3 should have been much higher than MIC or the former should have been cheaper than the latter to become an eco-efficient option.

From the given results, it can be inferred that eco-efficiency analysis can assist in the decision making process for choosing eco-efficient construction materials for green building design. These results can be beneficial in construction management to minimise their potential environmental impact in a cost effective manner.

FIGURE 11. Eco-efficiency portfolio of concrete beam mixes.



Social analysis

This section discusses the social implications of the use of eco-efficient concrete mix, M4. The structural suitability of M4 concrete mix, utilizing 50% recycled aggregates, in high end structural applications (i.e., beam requiring a compressive strength of ≥40MPa) could divert significant amounts of C&D waste from landfills. This will accelerate the growth of recycling industries in Western Australia.

Employment Opportunity—Capital Recycling in Perth employs 3 persons to produce 225 tonnes of recycled aggregates a day. Using this information, it is estimated that about 16 recycling companies could be developed in Perth to convert C&D wastes (i.e., 0.87 million tonnes per annum) (Instant Waste Management 2018) to recycled aggregates for concrete structural applications. These 16 recycling companies could potentially generate employment for around 48 people per year.

Avoided land use—Land use in both quarry and landfill locations can be conserved due to the conversion of C&D waste to recycle aggregates for concrete mixes. Following Shaikh et al. (2019), it is estimated that 0.55m^2 of land is required to produce 1 tonne of aggregates in WA. Therefore, 48 hectares of land use can be mitigated a year by substituting virgin aggregates in M4 with recycled concrete aggregates produced from 0.87 million tonnes of C&D wastes. Following Shaikh et al. (2019), a 64 hectare of landfill in Western Australia can hold 7,000 tonnes of wastes per year for 60 years. Using this information, it is determined that about 133 hectares of landfill area can be avoided by converting 0.87 million tonnes of C&D wastes into construction materials. Therefore, a total of 181 hectares (48Ha+133Ha) of land use could be conserved both at the quarry and landfill sites for future generations.

Energy conservation: Using a cumulative energy consumption (CEC) method in Simapro 8.4 LCA software, the CEC of per m^3 of M1C and M4 were calculated as 2,245MJ and 1,876MJ, respectively. Therefore, 369MJ amount of energy could be saved for future generations by replacing 1 m^3 of M1C with 1 m^3 of M4. It is estimated that about 1,468,354 m^3 of concrete beam mix can be produced a year from 0.87 million tonnes of wastes per year, which can result in the saving of about 1,50,506 MWh of electricity equivalent per year due to the avoidance of virgin aggregates production. Following Shaikh et al. (2019), it was estimated that this electricity could potentially meet the demand of around 50,168 houses a year; thus reducing the pressure on precious natural resources, while leaving adequate non-renewable resources for the future generations

CONCLUSIONS

This study confirms that the use of M2 (100%OPC+100%RA), M3 (90%OPC+10%SF+50%NA+50%RA) and M4 (60%OPC+30%FA+10%SF+50%NA+50%RA) concrete mixes exhibit a slight reduction in ultimate load capacity by about 15% compared to a control concrete beam under flexure. The failure behaviour in terms of cracking pattern of recycled aggregates concrete beams is very similar to that of a control concrete beam under flexure. Also, some of these RA based RC beams (M2and M3) exhibit about a 4–6% increase in ultimate load under shear. M4 shows about 25% reduction in ultimate load capacity under shear. All three types of recycled aggregate concrete beam mixes show very similar cracking behaviour under shear compared to a control concrete beam. Thus, it can be concluded that the RC beam specifications can be used in buildings.

M4 (50RA+50NA+60OPC+30FA+10SF) was found to be the only eco-efficient concrete beam mix. The replacement of controlled concrete (M1C) with M4 can help achieve an environmental benefit in a cost-competitive manner. The diversion of C&D wastes from landfill due to use of a M4 concrete beam mix could help create recycling industries and employment. Furthermore, about 180 hectares of land use can be avoided; thereby, conserving a resource for future generations, while also reducing the loss of biodiversity and vegetation (i.e., .151 GWh) with the replacement of energy intensive virgin aggregates.

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REFERENCES

ABS (2018). Australian Demographic Statistics, Dec 2018. https://www.abs.gov.au/ausstats%5Cabs@.nsf/mediareleasesbyCatalogue/CA1999BAEAA1A86ACA25765100098A47.

ABS (2019). Australian National Accounts: National Income, Expenditure and Product, Mar 2019. https://www.abs.gov.au/ausstats/abs@.nsf/39433889d406eeb9ca2570610019e9a5/78b08abe5e6f2df1ca2570d6001366dc!OpenDocument.

Arceo, A., M. Rosano, and W. K. Biswas (2018). Eco-fficiency analysis for remote area power supply selection in Western Australia. *Clean Technologies and Environmental Policy*, 20: 463–475.

Arezoumandi, M., et al. (2015). An experimental study on flexural strength of reinforced concrete beams with 100% recycled concrete aggregate. *Engineering Structures*, 88: 154–162.

Australian Government (2020). Electricity generation. https://www.energy.gov.au/data/electricity-generation.

Bengtsson, J., Howard, N. (2010a). A life cycle impact assessment method for use in Australia. Part 1: Classification and characterisation. Building Products Innovation Council, Australia.

Bengtsson, J., Howard, N. (2010b). A life cycle impact assessment method. Part 2: Normalisation. Building Products Innovation Council, Australia.

Biswas, W.K., Alhorr, Y., Lawania, K.K., Sarker, P.K., and Elsarrag, E. (2017). Life cycle assessment for environmental product declaration of concrete in the Gulf States. *Sustainable Cities and Society*, 35: 36–46. doi: 10.1016/j.scs.2017.07.011

Biswas, W.K. and D. Cooling (2013). Sustainability Assessment of Red Sand as a Substitute for Virgin Sand and Crushed Limestone. *Journal of Industrial Ecology*, 17(5): 756–762.

Clavreul, J., Guyonnet, D., and Christensen, T. (2012) Quantifying uncertainty inLCA-modelling of waste management systems, *J. Waste Manage.*, 32: 2482–2495.

Crossin, E. (2012). *Comparative life cycle assessment of concrete blends*. Melbourne, Australia: Centre for Design, RMIT University.

DIRD (Department of Infrastructural and Regional Development) (2017). Fright rates in Australia, Bureau of Infrastructure, Transport and Regional Economics (BITRE) GPO Box 501, Canberra ACT 2601, Australia https://bitre.gov.au/publications/2017/files/is_090.pdf

Dobbelaere, G. de Brito, and J. Evangelista, L. (2016). Definition of an equivalent functional unit for structural concrete incorporating recycled aggregates. *Engineering Structures*, 122: 196–208. doi.org/10.1016/j.engstruct.2016.04.055.

Goedkoop, M., M. Oele, J. Leijting, T. Ponsioen, and E. Meijer (2013). *Introduction to LCAwith SimaPro*, PRé, Netherlands.

González-Fonteboa, B. and F. Martínez-Abella (2007). Shear strength of recycled concrete beams. *Construction and Building Materials*, 21(4): 887–893.

González-Fonteboa, B., et al. (2009). Structural shear behaviour of recycled concrete with silica fume. *Construction and Building Materials*, 23(11): 3406–3410.

Guo, Z., et al. (2018). Mechanical properties, durability, and life-cycle assessment of concrete building blocks incorporating recycled concrete aggregates. *Journal of Cleaner Production*, 199: 136–149.

Homeone (2018). What is a reasonable builder's margin?, building and renovation company, Australia, https://forum.homeone.com.au/viewtopic.php?f=31&t=7566.

Hyder and Encycle Consulting (2011). Construction and demolition waste status report management of construction and demolition waste in Australia. Department of Sustainability, Water, Population and Communities, Australian Government.

Ignjatović, I.S., S.B. Marinković, and N. Tošić (2017). Shear behaviour of recycled aggregate concrete beams with and without shear reinforcement. *Engineering Structures*, 141: 386–401.

Instant Waste Management (2018). About Waste Recycling. Morley WA 6943 Australia. https://www.instantwaste.com.au/recycling/about-waste-recycling/. Accessed 30 May 2018.

Islam, H., Jollands, M., Setunge, S. (2015). Life cycle assessment and life cycle cost implication of residential buildings—A review. *Renew. Sust. Energ. Rev.*, 42: 129–140.

Ismail, S. and M. Ramli (2013). Effect surface treatment of recycled concrete aggregate on properties of fresh and hardened concrete. *Business Engineering and Industrial Applications Colloquium (BEIAC)*, 651–656.

Ismail, S., W.H. Kwan, and M. Ramli (2017). Mechanical strength and durability properties of concrete containing treated recycled concrete aggregates under different curing conditions. *Construction and Building Materials*, 155: 296–306.

ISO14040 (2006). ISO 14040:2006—Environmental Management—Life Cycle Assessment—Principles and Framework, International Organization for Standardization, Geneva.

Katkhuda, H. and N. Shatarat (2016). Shear behavior of reinforced concrete beams using treated recycled concrete aggregate. *Construction and Building Materials*, 125: 63–71.

Kicherer, A., Schaltegger, S., Tschochohei, H., & Pozo, B.F. (2007). Eco-efficiency. *The International Journal of Life Cycle Assessment*, 12:537–543. doi: 10.1065/lca2007.01.305

Leek, C. and Huband, A. (2010). Recycled products in local road construction and maintenance activities, prepared for WALGA.

Life Cycle Strategies Pty Ltd. (2015). Australasian Unit Process LCI Library and Methods. Version 2015_02_06. http://www.lifecycles.com.au/#!australasian-database/cbm5. Accessed 30 Jun 2015.

Master Builders (2014). Smart Waste Guide. http://www.mbawa.com/wp-content/uploads/2014/09/Smart-Waste-Guide-resized.pdf.

Ozbakkaloglu, T., A. Gholampour, and T. Xie (2018). Mechanical and Durability Properties of Recycled Aggregate Concrete: Effect of Recycled Aggregate Properties and Content. *Journal of Materials in Civil Engineering*, 30(2).

Pedro, D., J. de Brito, and L. Evangelista (2018). Durability performance of high-performance concrete made with recycled aggregates, fly ash and densified silica fume. *Cement and Concrete Composites*, 93: 63–74.

Pickin, J. and P. Randell (2016). Australian National Waste Report. Department of the Environment and Energy. Australian Government.

Pons, O. and A. de la Fuente (2013). Integrated sustainability assessment method applied to structural concrete columns. *Constr Build Mater*, 49: 882–93.

Pré Consultants (2018). *SimaPro database*. Pré Consultants, The Netherlands.

Renouf, M.A. (2015). *Best practice guide for life cycle impact assessment (LCIA) in Australia*. Australian Life Cycle Assessment Society, Australia

Sato, R., et al. (2007). Flexural Behavior of Reinforced Recycled Concrete Beams. *Journal of Advanced Concrete Technology*, 5(1): 43–61.

Shaikh, F.U., Nath, P., Hosan, A., John, M. & Biswas, W. (2019). Sustainability assessment of Recycled Aggregates Concrete mixes Containing Industrial By-Products. *Materials Today Sustainability* online: 1-1.

Synergy (2018). Important information about changes to electricity rates, Perth, Australia, https://www.synergy.net.au/Global/ARP18-Price-changes.

T Kang, Thomas H.-K.; Kim, Woosuk; Kwak, Yoon-Keun; Hong, Sung-Gul (2014). Flexural Testing of Reinforced Concrete Beams with Recycled Concrete Aggregates (with Appendix). *Structural Journal*, 111(3).

Tai, J., M. An, and X. Wang (2017). *Annual research report on the development of urban environmental and sanitation industry in China: 2015–2016*. Shanghai Jiao Tong University Press, Shanghai.

Wang, J.J., Wang, Y.F., Sun, Y.W., Tingley, D.D., and Zhang, Y.R. (2017). Life cycle sustainability assessment of fly ash concrete structures. *Renewable and Sustainable Energy Reviews*, 80: 1162–1174.

Waseem, S.A. and B. Singh (2016). Shear transfer strength of normal and high-strength recycled aggregate concrete—An experimental investigation. *Construction and Building Materials*, 125: 29–40.

Waste Authority (2012). Western Australian Waste Strategy: "Creating the Right Environment," Waste Authority Western Australia.

Waste Authority (2016). Waste Authority Position Statement Construction and Demolition (C&D) Waste.

WBCSD (2009). *Recycling Concrete*. The Cement Sustainability Initiative. Geneva, Switzerland. p. 1-51.

WMR (Waste Management Review) (2015). Report shows WA falling short on recycling targets, http://wastemanagementreview.com.au/wa-recycling-report-2015/.

Xie, J., et al. (2018). Experimental study on the compressive and flexural behaviour of recycled aggregate concrete modified with silica fume and fibres. *Construction and Building Materials*, 178: 612–623.

Yoshida, H., Christensen, T.H., and Scheutz, C. (2013). Life cycle assessment of sewage sludge management: A review. *Waste Manag Res.*, 13: 1083–1101.