A framework for the integrated cost-benefit analysis of the use of recycled aggregate concrete in structural applications

Mayuri Wijayasundara, Priyan Mendis and Robert H. Crawford
The University of Melbourne, Melbourne, Australia
gww@student.unimelb.edu.au, pamendis@unimelb.edu.au, rhcr@unimelb.edu.au

Abstract: Recycled concrete waste in the form of recycled concrete aggregate (RCA) is presently used mostly as a road base filler replacing natural aggregate in Australia. However, instead of manufacturing Natural Aggregate Concrete (NAC) using Natural Aggregate (NA) as a constituent material to use in structural applications, there is potential to use RCA replacing NA to manufacture Recycled Aggregate Concrete (RAC). This paper presents a framework to estimate the costs and benefits of producing RAC, against producing NAC. The framework applies to the system boundary of production processes of RAC, NAC and the life cycle of their respective constituent materials. Cost-benefit assessment (CBA) is identified as an appropriate method to evaluate the internalised impacts as well as external costs concerning the use of both RAC and NAC. This paper proposes a framework to cover the primary impacts which are directly attributable to the RAC or the NAC, as well as the secondary impacts which results in the immediate boundary due to the proposed changes using CBA. The basic methodology for the evaluation of the above impacts considering technical, financial, environmental and social perspectives to obtain a comparable value is discussed in the paper.

Keywords: Recycled aggregate concrete; cost-benefit analysis.

1. Introduction

Concrete waste is recycled to produce Recycled Concrete Aggregate (RCA) which is currently used as a road base product in Australia. The research suggests that out of the entire world’s production of RCA, 99% is used for low value applications (Tošić et al., 2015), which include the use as a road base material or a filler material for pavement bases. The use of RCA in structural applications as a replacement material for coarse natural aggregate (NA) has gained wider interest as it suggests advantages in many fronts. These include 1) providing a sustainable end use to the concrete waste in the construction and demolition (C&D) waste stream, 2) addressing natural aggregate scarcity and 3) conservation of natural aggregate. Weighing the many advantages brought about by the promotion of the replacement of natural coarse aggregate in structural concrete, several investigations have been conducted over the
last decades to characterise RCA as a constituent material for concrete and to determine the level of performance of the resultant concrete, called as recycled aggregate concrete (RAC).

To produce RCA as a coarse aggregate, the fine aggregate needs to be separated following the typical two stage crushing process used to make RCA (Dosho, 2007). The crushing process results in micro cracks in the surface and produces a material that consists of two visible phases, namely the natural aggregate phase and the residual mortar phase. The parent concrete is crushed and the fine recycled concrete aggregate (FRCA) which are particles typically less than 5 mm are separated out in the process. The coarse RCA is generally identified in research as a material which is 1) porous, 2) non-homogeneous, and 3) of variable quality compared to NA. (Poon et al., 2004). One of the key challenges in using RCA for concrete is to deal with the high water absorption associated with the presence of a porous structure in the RCA, compared to the NA it replaces in concrete. The high water absorption primarily deteriorates the workability of the concrete (Behera et al., 2014).

Characterising the use of RCA in concrete, the research conducted so far, is more inclined to use it in low-medium strength applications (<40 MPa) and to adopt rates of replacement less than 30%. This is in line with the current Australian Standard, HB155:2002, which recommends the use of RCA for applications less than 40 MPa in strength at a maximum rate of replacement of 30% (Commonwealth Scientific and Industrial Research Organisation, 2002). Commercial production of RAC and the use of it for structural applications have not taken place so far at industrial scale in Australia, though industrial trials are reported. Amalgamating the findings of the research conducted so far, it is important to evaluate the position of the use of RAC in structural applications, against the current practice of the use of NAC.

2. Background

There are several studies which have evaluated the use of RAC against NAC, and RCA against NA focusing on different dimensions. Vivian (2008) has conducted an economic comparison of recycling of concrete and concluded that recycling of concrete is economically beneficial (Vivian, 2008a). The study has taken into consideration the avoided effect from landfilling considering the landfill to represent an economic cost. The study is limited to the recycling of concrete to produce RCA. Marinkovic et al. (2009) and Knoeri et al. (2013) conducted a comparative environmental assessment to compare the environmental impact of the use of RAC compared to NAC (Marinković et al., 2010; Knoeri et al., 2013). Estanqueiro (2012) have conducted a life cycle assessment of the use of RCA and NA in concrete (Estanqueiro, 2012). Duran et al. (2006) has presented a model for assessing economic viability of C&D waste recycling options (Duran et al., 2006). These studies have provided insights on evaluating one single criterion or part of the system boundary concerned, yet a complete analysis of the alternatives is still required.

Nicola et al. (2015) conducted a multi-criteria optimisation of NAC and RAC with the purpose of finding the optimal type of aggregate. The study used a normative multi-criteria optimisation method involving technical, economic and environmental aspects. NAC made with river aggregate resulted in the cheapest option, while RAC with RCA replacement of 50% was the overall optimal solution (Tošić et al., 2015). This is considered an important step forward in incorporating multiple disciplines simultaneously, to analyse the two alternatives. However, while the study used a specific case study, the detailed conceptualization of the problem in the general context was not present. Inclusion of commercial production complexities and valuing indirect and social components were also not addressed in this study.
2.1. The importance of an integrated evaluation framework

It is identified that a multi-disciplinary approach is required to compare RAC against NAC. This is due to the fact that, the assessment of material performance, environmental benefits and the financial viability individually, does not converge to provide a conclusive outcome; to decide between the two alternatives.

In general, RAC cannot be considered as a technically superior material compared to NAC for the purpose of using it in structural concrete. Unlike the other supplementary cementitious material (SCM), such as ground granulated blast-furnace slag (GGBS), fly ash (FA) and phosphorous slag (PS), that favours the pozzolanic reactions in concrete and improves the properties and performance, RCA as a replacement to coarse NA is not visibly advantageous in terms of the material performance of concrete (Wang et al., 2013). It brings complexity to the concrete mix as well as the processes of preparation (Li et al., 2012; Behera et al., 2014). Equally it provides little flexibility for adoption in the industry reliably as the applications are limited with the exclusion of higher strength classes and special concrete types and with a recommendation to apply in lower replacement rates (Limbachiya et al., 2000). Therefore, use of RCA in structural concrete is not driven by the purpose of providing an improvement to the concrete performance unlike for alternatives such as pozzolanic materials.

Considering the environmental perspective, the use of RAC is considered to provide multiple environmental advantages (Behera et al., 2014). However, when the direct environmental impacts are assessed in detail, the advantages were not clearly visible. Marinkovic et al. (2010) in his study comparing the environmental impacts of RAC and NAC concludes that the results depend largely on the transport distances and favor the use of RAC when the difference of transportation distance of RCA is 20 km less than that of NA (Marinković et al., 2010). The results are based on mixes with an additional 5% of cement. Knoeri (2013) extends the results by incorporating the avoided impacts of steel and fly ash and concludes that until RAC uses an additional 10% cement, the situation favors the use of RAC (Knoeri et al., 2013).

On the other hand, with the extent of processing required, and accounting for the changes in mix design and adaptation costs, 0-20% price difference between RCA may/may not make RAC a cheaper option. To make it further complicated, some elements affecting material performance are interlinked with other aspects, such as addition of supplementary cement to RAC. It would favor the material performance in terms of compressive strength enhancement, but compromises both the environmental and financial outcomes.

While some of the advantages associated with the use of RAC in structural applications are quantified in previous research, some are qualitatively evaluated. Therefore, an integrated framework which interlinks the design aspects of the material and the manufacturing process, to the environmental, financial and other qualitative aspects which are not quantitatively evaluated so far is required, in order to comprehensively evaluate the two alternatives. This paper proposes Cost-Benefit Analysis (CBA) to evaluate and bring the critical parameters concerned to a common base for comparison.

2.2. Aims and scope of research

The research presented in this paper aims to:
establish criteria to evaluate the use of recycled concrete aggregate (RCA) to manufacture recycled aggregate concrete (RAC); compared to the use of natural aggregate (NA) in manufacturing natural aggregate concrete (NAC); to use in structural concrete, covering all significant implications

propose a framework and outline methodology to evaluate the outcome of the above two alternatives using cost-benefit analysis (CBA)

3. Methodology

This section presents the research approach used to address the above mentioned aims of the study.

3.1. Proposed method for evaluation – Cost-benefit analysis

The common tools used for evaluation of alternatives as above are environmental impact assessment (EIA), strategic environmental assessment (SEA), life cycle analysis (LCA), risk assessment (RA), risk benefit assessment (RBA), cost effectiveness analysis (CEA), multi-criteria analysis (MCA) and CBA (Pearce, 2006).

CBA is selected out of the above approaches for several reasons. Firstly, considering the need to assess the monetary aspect, methods which disregard monetary aspects and costs such as EIA, SEA and LCA were not considered. LEA with life cycle cost analysis was not considered as the evaluation requires economic evaluations, in addition to cost analysis with environmental data. RBA is similar to CBA if the identified risks are monetised. CEA requires the assumption of a single indicator of effectiveness which would lack representation of all concerned variables. Multi-criteria analysis (MCA) is similar to cost effectiveness analysis yet involves multiple indicators of effectiveness. MCA differs from CBA with the distinction coming from the fact that not all criteria are monetised. The final outcome of MCA is the weighted average of the scores, relating to multiple objectives. MCA therefore offers broader interpretation, better transparency of the results against particular criteria and flexibility to make decisions considering one dimension as a more important one. However, MCA does not offer decisions on whether to carry out a project or not, especially if the results of each objective would offer different directions. Lack of cohesion of the decision variable is, therefore, a disadvantage of MCA compared to CBA.

As a basic analysis method which provides an absolute value for comparison integrating a number of different aspects into one result, CBA is chosen to evaluate the outcome of the study. However, CBA could be subjective in monetising qualitative aspects and is not transparent as to what would be the trade off with other dimensions, unless they are considered separately. The main outcome of CBA is the net present value (NPV), which is the difference between the value of all benefits and the value of all costs discounted to the present. A positive value of NPV indicates an economically viable project. A few important things to note in CBA are: 1) benefits to the wider society are considered rather just the profit of parties involved in a change; 2) non-financial perspectives are incorporated; 3) non-financial perspectives are monetised for comparison.

CBA measures the costs and benefits considering “an economic” point of view (e.g. benefit and costs to society) as well as “a financial” point of view (e.g. revenues and costs only to investors). It is important to highlight the difference in fundamentals between the economic and financial perspectives to understand this. “Financial” usually refers to money matters relating to transactions of some size or
importance, and it is generally associated with a specific party under consideration. The main bottom line indicator from financial analysis is generally given by profit, where;

\[ \text{Profit} = \text{Revenue} - \text{Cost} \]  

(1)

As an example, in evaluating a change such as the one associated with the RAC and the use of NAC, the financial implication can be presented as;

\[ \text{Profit from a unit of concrete (Contractor)} = \text{Price of a unit of RAC} - \text{Price of a unit of NAC} \]  

(2)

However, an economic system has a much broader definition. Economy is defined as the process or system by which goods and services are produced, sold, and bought, in a country or region (Merriam-Webster, 2015). The Government of a country is the regulator of a country's economy and the primary purpose of the government is the well-being of the society. Hence, a change is evaluated from the point of view of change of a policy, project or an initiative and the bottom line indicator is the net benefit to the society, where;

\[ \text{Net benefit} = \text{Benefits} - \text{Costs} \]  

(3)

As an example, the economic implication associated with the use of RAC as opposed to NAC for a unit volume of concrete can be presented by;

\[ \text{NPV from a unit of concrete (Society)} = \text{Net benefit from a unit of RAC} - \text{Net benefit from a unit of NAC} \]  

(4)

While for some dimensions, readily estimated financial figures in valuing costs and benefits are available, some require valuation. Non-market costs and benefits, which do not have a readily available value for exchange in the market, require valuation using techniques such as willingness to pay (WTP) for a benefit and willingness to accept (WTA) a cost.

The basis of CBA is to establish that the costs and benefits would accrue over time as a result of a project or an initiative and to discount them to the present time to produce an absolute value. Therefore, CBA provides a net present value (NPV), taking into account the time value of money.

Therefore, considering the above example, RAC is viable to society if:

\[ \text{Net present value of RAC} > \text{Net present value of NA} \]  

(5)

However, the construction contractor would find it viable when,

\[ \text{Cost of producing RAC} < \text{Cost of producing NAC} \]  

(6)

Therefore, if Equation 6 is not valid, a construction contractor as a party conducting business for monetary gains would not be encouraged to buy the product. As a result the upstream supply chain
which involves the demolition contractor, recycler and the ready-mix concrete (RMC) manufacturer is not encouraged to produce the inputs for the product or the product itself. However, if Equation 5 is valid, society benefits from the manufacture of the product. In such a situation, intervention of the Government as the regulator of the economy would be required to incentivise production of the product.

3.2. Framework for economic evaluation of RAC and NAC

The paper proposes a framework for the evaluation of four variables mentioned in Equations 5 and 6 above. Application of the framework requires consideration of the boundary of two main operations and the cradle-to-gate life cycle impact of the constituent materials used for those two operations. They are, namely, 1) production of NAC using constituent materials for concrete with NA as a constituent material, and 2) production of RAC considering NA and RCA as constituent materials (with RCA replacing NA partially).

Moving to RAC could have impacts on the main operation of producing concrete, which are considered as primary impacts, and impacts on the related products, by-products and waste in the immediate boundary of operations considered as the secondary impacts. The primary activities covered in the system boundary of NAC and RAC are presented in Figure 1. The recycling operation of RCA as a road base material, and transportation of concrete waste to landfill, located outside the boundary are two operations considered as secondary impacts. The secondary impact arises as a material volume needs to be reduced from one option (concrete waste sent to landfill) in the immediate boundary for it to be used in another option (concrete waste recycled to produce RCA for concrete).

![Figure 1: Boundary of primary activities of producing RAC and NAC.](image-url)
Extraction of NA rock and aggregate processing are needed to produce NA; and NA needs to be transported to a RMC manufacturing plant and mixed with other constituent materials such as cement, fly ash, slag, water, fine aggregate and additives to make NAC. These are presented as primary activities of NAC production, inside the concerned system boundary in the bottom part of Figure 1.

The top part of Figure 1 presents the system boundary of the primary activities for RAC. The concrete waste would be recycled at a recycling plant to produce RCA suitable to be used in concrete. The RCA produced as a constituent material for concrete will replace x% of the coarse NA requirement in concrete, while the balance (100-x) % will be NA. The RAC would also be manufactured in a RMC manufacturing plant, but would use a different mix consisting of the same materials to account for the incorporation of RCA in the mix. The processes are also expected to be different to that of the typical NAC manufacturing process. With the change of the concrete mix in the two cases, the quantities of other constituent materials required will also be different, and their life cycle impacts must be incorporated. For simplicity, the upstream processes of the constituent material production are not presented in the two system boundaries presented in Figure 1.

3.3. Application of the framework

Figure 2 presents a framework for the evaluation of two main categories of implications associated with RAC as opposed to NAC. These changes are indicated by the changes in material flow within the mentioned system boundaries above. They are 1) internalised impacts and 2) externalities. Internalised impacts are the ones that have been accounted for monetarily in the pricing system, with the parties involved gaining or losing monetarily due to the change. Externalities on the other hand, are defined as an effect that production or consumption has on third parties who are not involved with production or consumption (Boardman et al., 2011).

In other words, internalised impacts reflect the financial value, either surplus/deficit whereas the externalities reflect external cost not captured by the pricing system. The next step is to categorise externalities into: 1) direct environmental, 2) indirect environmental and 3) social segments for the purpose of evaluation. The primary activities resulting from the change will give rise to direct environmental externalities, while the secondary activities will result in indirect environmental externalities. The sum of the above three elements will produce the net external cost/benefit to society with the production of a unit volume of RAC. The basic methodology for the evaluation of the above four impacts are stated in the next two sections.

3.4. Technical assessment for the manufacturing of RAC

In order to estimate the above impacts, the industrial scale production environment of recycling and RMC manufacturing operations has to be simulated. Firstly, a technical assessment is conducted for this purpose to state the changes required in the mix, manufacturing environment and the industrial material flows.

The evaluation of the manufacturing environment is based on the operations of a typical concrete recycling plant producing RCA to be used as a road base material and a typical RMC plant producing NAC, and assessing the changes required to manufacture RAC. In order to produce RCA to be used as a constituent material in concrete, which will have: 1) less contamination, 2) less fines, and 3) a different grading and size requirement, the operations of the recycling plant would need to change. While the crushing process would remain the same, size separation and quality control processes are assumed to
be different. In a RMC manufacturing plant, the material receipt, quality control, storage, material preparation and mixing processes are expected to change, requiring additional infrastructure and process modifications. Therefore it is assumed that additional cost and energy consuming activities will be required at the concrete recycling plant and RMC manufacturing plant.

![Figure 2: Main framework associated with cost-benefit analysis for comparing production of RAC against NAC.](image)

The concrete mix using RCA would be different to that of NA, to account for the different quality of the aggregate with attached residual mortar. The change of mix constituents involve inclusion of supplementary cement and cementitious material, addition of mineral and chemical admixture (Behera et al., 2014). In addition to altering the mix constituents in concrete, preparation and mixing techniques are suggested to improve the performance of the resultant RAC (Tam et al., 2007b). Based on the quantities required and the changes in the manufacturing environment, the material flow diversions are estimated next, as a result of producing RAC.

3.5. Evaluation of financial and direct environmental impacts

The financial impact is assessed as the incremental financial cost for RAC, estimated based on the changes proposed in the technical assessment. The incremental financial cost would include the incremental material cost (IMC) and the incremental processing cost (IPC), with a margin added to it. IMC of RAC results due to the change of mix, incremental pre-processing cost of RCA and the incremental transportation cost of RCA, whereas the IPC would result due to the incremental processing cost in RMC manufacturing. IPC is estimated via process based costing (PBC) method, based on the incremental process changes and infrastructure requirements.

The direct environmental is captured by estimating the embodied energy (EE) in RAC primarily. For this purpose, incremental EE of RAC compared to NAC is evaluated using input-output (I-O)-based hybrid method and is converted to CO₂ emissions, based on emissions per fuel mix assumptions. CO₂ emissions are monetised, based on a charge per MT, to provide the monetary value to the integrated result.
3.6. Evaluation of indirect environmental and social impacts

The secondary environmental impacts in the boundary presented in Figure 1, are identified as indirect environmental impacts. For example, concrete waste for producing RCA results due to diverting the C&D waste originally sent to landfill, and the replacement of NA by RCA, reduces use of NA, thereby reducing NA extraction. The avoidance of landfill of C&D waste and avoidance of NA extraction are therefore considered as indirect environmental benefits as a result of producing RAC, and evaluated using economic valuation methods. Adjusted transfer technique in benefit transfer method is suggested to evaluate the specific values of those, based on the previous evaluations conducted on estimating the environmental cost of these impacts separately.

Social impacts of producing RAC would be evaluated qualitatively under this methodology.

4. Results and discussion

The above concept, framework and basic methodology can be used to conduct CBA, to evaluate four main elements, to compare the use of RCA in manufacturing RAC against the use of NA in manufacturing NAC.

- The internalised impact estimates the financial cost/cost saving in producing a unit volume of RAC. This is evaluated by incorporating the incremental material cost and the incremental processing cost to manufacture RAC, resulting due to the changes in the production chain of RAC compared to that of NAC.
- The direct environmental impact is obtained by estimating the incremental EE of RAC compared to NAC. Using I-O-based hybrid method, EE of RAC compared to NAC is to be evaluated and the result is to be converted to CO$_2$ emissions and then to a monetary value.
- The indirect environmental impact is evaluated using economic valuation methods by considering the secondary impacts of manufacturing RAC. Avoidance of landfill, NA extraction etc. require evaluation using benefit transfer method, by obtaining previous values and conducting adjustments to match to the context.
- The social impact is to be evaluated qualitatively.

5. Conclusions

The following concluding remarks can be made from the above discussion.

- A comprehensive evaluation is required covering multiple dimensions to compare the use of RCA to manufacture RAC, against the use NA to produce NAC for the same purpose. This is because when the material performance, environmental benefits and financial viability are generally looked at there are trade-offs of one aspect or the other and there are complex interlinks within these.
- CBA is identified as an effective method to estimate the quantitative as well as qualitative aspects concerned with the use of RAC. CBA monetises the qualitative and non-financial aspects and brings them to present value terms considering the time value of money.
- The need to consider both the financial aspect which reflects the monetary gain to the concerned party as well as the externalities which reflect the benefits gained to the society is identified for this type of problem, as the pure financial drive may not lead to production of RAC.
A framework incorporating internalised impacts and externalities is proposed to evaluate the production of RAC against NAC. The internalised impacts are reflected by the financial gain/loss with the production of a unit volume. The external impacts are categorised into direct environmental, indirect environmental and social impacts. This paper proposes a methodology to evaluate each of them considering the concerned system boundaries for both cases. The framework and approach proposed in this paper are critical for evaluating and selecting of preferred concrete types for use in buildings as structural concrete. This is important information for building designers and engineers as they strive to reduce the environment impact of the built environment.

6. Limitations

The methodology requires adoption of different scientific methods, from different disciplines to evaluate each dimension. At the point of integration of the results, bringing them to a common base is a complex task. As an example, the results from economic evaluation would require the results to be brought to present terms, accounting for discounting and to be indicated by monetized value per unit volume of RAC. The results derived from environmental data (such as CO₂ emissions), especially under the direct environmental impact assessment would have uncertainty associated with the timing of effects, such as the emissions resulting from upstream processes. Equally, in evaluating the indirect environmental impacts, the subjectivity arising from the use of benefit transfer technique in economic valuations would affect the results. This is due to the inability to do adjustments to perfectly match to the context of the original study, and therefore, disregarding the key assumptions made in the original valuations.

7. Recommendations for further research

While there can be recommendations for further research suggested for each discipline considered, this paper would limit the suggestions made to the integrated framework. Firstly, in the technical assessment, different options for scaling up of the RAC manufacturing environment can be explored. Considering customized operations for the preparation of RCA as a constituent material in concrete, up-scale impacts of having these operations as an extension to the concrete recycling or RMC industries need to be investigated. Secondly, dynamic material flow simulations with varying composition of concrete waste diverted to produce RCA as a constituent material for concrete could be conducted using a method such as system dynamic modelling. This study together with a demand-supply assessment on the requirement for RCA to replace NA would add value to understand the industry material flow impacts with the implementation of the initiative.

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References


