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Research article

Cost-benefit analysis of the production of ready-mixed high-performance concrete made with recycled concrete aggregate: A case study in Thailand

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ABSTRACT

In the current green concrete structures, recycled concrete aggregate is used as recycled concrete waste. In this process, concrete waste is collected and crushed using a recycling procedure in order to produce crushed concrete which is then used in structural concrete where it replaces natural aggregate which is coarse. The recycled aggregate concrete is a sustainable concrete waste which in the long term can replace the demand for natural aggregate, a process which would, in turn, lead to its preservation. However, most concrete industries have been observed to be reluctant in the production of recycled aggregate concrete and utilization in its maximum potential. Industries are yet to embrace it not only due to its uncertain material performance but also due to its unexplored manufacturing plant operations which are yet to be established. This research aims to use of a cost-benefit analysis model of the production of ready-mixed high-performance concrete made with recycled concrete aggregate in Thailand. The model focuses on the evaluation of the financial effects which favor the recycled aggregate concrete manufacturing operations instead of the ordinary concrete. Research findings indicate that regardless of the manufacturing plant used, the price of recycled concrete aggregate cannot decrease below the price of natural aggregate concrete. The key result of this research is that recycled concrete aggregate manufacturing set-ups can be used in the industrial-scale manufacture of recycled concrete and at low prices. In addition, overhead bin type and front-end loader type of plants can be used to lower the incremental costs of recycled concrete aggregate. However, the demand and supply factors and the pricing effects of recycled concrete pose various difficulties which are hardly accounted for.

1. Introduction

The rising concerns of the environmental damage caused by the use of natural aggregate has led to interests in more conservative and cost-effective concrete materials such as recycled aggregate concrete. Recycled concrete aggregate (RCA) has the potential to replace natural aggregate concrete due to its wide range of benefits and low cost of manufacture. However, there is minimal usage of recycled aggregate concrete in constructions as people are still unaware of its cost-benefit advantages and its manufacturing process. According to Wijayasundara et al. (2016), reinforced concrete with demolition waste has been approximated to have about 50% concrete waste when measured in terms of weight. Denoted as CC, crushed concrete is produced from the processed concrete waste and the coarse portion of it is separated since it is regarded as an aggregate product and is known as RCA (Manzi et al., 2017). On the other hand, the fine portion of the product is known as fine recycled concrete aggregate and is abbreviated as FRCA. When RCA is replaced with natural aggregate (NA) in concrete, the resulting product is recycled aggregate concrete (RAC).

RCA in concrete is currently more inclined to applications with low to medium strength and which can adapt to minimal replacement rates of up to 30 wt.% (Xiao, 2017). Ongoing research is focusing on improving the performance of RCA as a product and to address the rising questions on whether RAC should be promoted in concrete production against natural aggregate concrete (NAC) (Verian et al., 2018). RAC has in the past been identified to be inferior to NA in concrete production regardless of its positive environmental performance. However, the production of RAC does not currently come with favorable financial outcomes to the manufacturer (Zaetang et al., 2016). This is because the production and adoption prices seem to outweigh the cost difference observed between the two products (Peng et al., 2020). In addition, RAC has many disadvantages and is known for its high porosity if used with high w/c ratio

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(Dimitriou et al., 2018). However, most countries including Thailand and other communities that are resource-constrained have been using NAC which has various sustainability issues. Also, the construction operations in these communities are leading to the emission of a lot of concrete waste and green-house gasses which affect the environment. The continuous production of concrete in the form of cement in these countries is harmful and unsustainable since it continuously depletes the available natural resources (Chatterjee and Sui, 2019). Due to these and other factors, there is a rising need to implement effective and environmental-friendly solutions such as the production of RCA. Therefore, in order to overcome the rising concerns of RAC disadvantages, an integrated assessment needs to be conducted in order to evaluate the relevant dimensions needed to evaluate RAC utility against its rival product NAC.

Lack of knowledge on the cost-benefit perspectives to the manufacturing of RAC is a serious matter that requires full attention due to its impact on industry dynamics (Hemalatha and Vani, 2018). Currently, it is not known whether processing, quality control, and adoption costs in a standard RAC manufacturing plant outweigh the benefits that arise from RCA obtained as a low price constituent material in concrete (CMC) in comparison to NAC. The already existing large ready-mixed concrete (RMC) manufacturing companies are one of the reasons behind the slow industrial uptake for the manufacturing of RAC (Serres et al., 2016). However, current trends where RAC is gradually replacing NAC in various structural developments have increasingly gained significance due to certain reasons. For instance, it encourages recycling as opposed to landfill disposals and enables sustainability for concrete waste (Wu et al., 2018). In addition, it has drastically reduced the NA demand, has addressed NA scarcity and, finally, it has enabled the conservation of quarried NA (Bui et al., 2018). These and many other advantages have led to rising concern for the production and use of RAC in structural developments despite the cost.

A key disadvantage associated with the use of RCA in concrete is the rising pressure to deal with high porosity and absorption of water due to the presence of a porous material in RCA (Shi et al., 2018). The high rate of absorption of water in RCA reduces the workability of the concrete material and needs to be dealt with in order to increase its efficiency (Namarak et al., 2018). RCA needs to be manufactured as a CMC using the concrete waste recycling process which can effectively reduce cost. Interestingly, the rate at which construction and demolition waste (C&D) is being recycled stands slightly above 50% in most countries while others have higher recycling rates of up to 80 and 90% (Wijayasundara et al., 2017). The present commercial concrete manufacturing context can provide for the immense improvement of C&D waste recycling in order to promote the industrial production of RAC (Younis et al., 2018; Zhan et al., 2019). However, the financial considerations for the manufacturing of RAC in the already existing RMC plants need to be considered in order to produce RAC. The financial considerations for the effective manufacture of RAC will pave way for the development of RAC markets in Thailand.

Besides cost issues that limit communities from implementing effective and environmentally friendly resolutions such as RCA, poverty has been observed to imposes unique constraints that lead to delay and at times no plans to implement various engineering operations. With the construction industry being one of the most important industries that contribute to economic growth in a country, poverty can lead to constraints that can limit construction plans (Durdyev et al., 2017). Areas characterized by these resource constraints are commonly affected by poverty which, in turn, results in failure of plans and already implemented construction operations. Global engineering frameworks and policies need to be implemented in the affected areas to foster better development and improve the economy (Raymond et al., 2017). The constraints imposed by poverty include poor infrastructure required to access remote areas, poor facilitation of international trade, and poor road safety measures (O'Donnell et al., 2019). Unavailability of proper infrastructure that can enable access to remote areas has a great effect on resource-constrained communities where it is difficult to access the little resources available (Hall-Andersen et al., 2016). There is a need for strong community-wide leadership, accountability, and coordination in these areas to deliver improvements by implementing better engineering plans such as recycling concrete. Also, the international trade constraint is impacting resource-constrained areas as they are unable to trade the little resources they possess (Deakins and Bensemann, 2019). This can be solved by improving access to these areas by building cheaper roads which can ultimately lower costs.

According to Forsyth (2018), Thailand is in the process of transformation and development and is looking forward to the elimination of the resource constraints that lead to a lack of RAC markets in the country. There is a rising need to impose a new and effective engineering solution that can work for all resource-constrained communities (Lacy and Rutqvist, 2016). Thailand began its exposure to concrete waste recently and is not optimally recycling or managing concrete waste. Current concrete waste operations in Thailand have resulted from the demolition of old buildings that have been torn down to pave way for the construction of modern buildings (Srivastava et al., 2019). These operations which involve large constructions in warehouses and industrial plants have led to major environmental issues related to construction wastes. These demolitions which are being used primarily because of lack of better concrete plans such as RCA are affecting the poor by destroying their cheaper homes and introducing modern houses that are unaffordable (Sopapornamorn et al., 2016). Lack of better engineering operations such as the manufacture of RCA is continuously affecting the poor by degrading natural resources and emitting waste into the environment. This is resulting from the constant poor management of waste and demolition of natural resources through excavation and demolition (Martos et al., 2018). Such operations are leading to destruction and loss of the readily available resources in the resource-constrained communities (Hui et al., 2018). To solve this, Thailand and other areas that are affected by resource constraints need to implement new RCA manufacturing methods. Silva et al. (2017) state that these methods are cost-effective and environmental friendly since RCA reduces the emission of waste by encouraging recycling. The introduction of cost-benefit analysis of RCA manufacturing plants that produce high-quality concrete and other concrete products will come in handy due to the new construction plans in Thailand (Mulenga et al., 2018). The expansion of the housing construction and the need for new and better built-in condominiums that can meet the needs of families will lead to the increasing demand for construction materials. Concrete obtained from the construction materials in the demolished building can be crushed into smaller sizes according to the preferred standards (Perera et al., 2019). According to Amorim Júnior et al. (2019), the RCA can be used to replace NA by applying RCA in the concrete mixture and using the prescribed ratio. This is a cheaper method that can be applied in resource-constrained areas to limit the emissions and demolitions that affect the poor.

Due to the unavailability of cheaper and environmental-friendly engineering solutions in these resource-constrained communities, critical issues of sustainability are constantly affecting them. A study conducted by the Pollution Control Department which operates under the Ministry of Natural Resource and Environment defined the effects of solid waste management from the undergoing demolitions in Thailand (Pharino, 2017). The study highlights that sustainability issues arise as a result of solid waste originating from the construction sites which is proving difficult to manage. This waste is being disposed of in empty spaces, in public places, and into rivers, thus, affecting the resource-constrained communities (Thongkamsuk et al., 2017). According to Yadav and Samadder (2018), construction waste is a common problem in communities that are looking forward to implementing rapid expansion which requires large-scale construction operations. Infrastructure expansion operations conducted in residential, industrial, and business areas are severely affecting the current drainage systems which have been observed to overflow (Meneses et al., 2018). The disposed solid waste elements from these construction operations include plastic, paper, steel, sand, soil, concrete, bricks, stones, and non-metallic materials (Babel et al., 2020). The sustainability of these operations which are mostly affecting the resource-constrained areas is leading to a slow rate of growth in the society, destroying the well-being of the planet, and slowing human development (Malinauskaite et al., 2017). Lack of RCA in these areas means that they are using excessive NCA which releases greenhouse gases such as CO_2 and other greenhouse gases (Rajaeifar et al., 2017). Also, the sustainable production of NA is in question since it continuously depletes the natural resources most of which are essential for its production. According to Ahrari and Haghani (2019), the resource-constrained areas are seen to be in heavy consumption of cement which are required for use in the expansion plans. However, the supply of large quantities and good quality limestone which can produce cement is continuously decreasing (Kang et al., 2019). Soon, the production of adequate amounts of cement for use in the expansion operations will become extremely difficult. Therefore, the resource-constrained areas must implement sustainable solutions for future construction operations using concrete.

RAC is made with RCA which occurs from recycled aggregate, a component that can also precipitate recycled concrete buildings and infrastructures. Since the early 1970s, the United States among other countries has been witnessing the occurrence of recycling concrete and asphalt until the early 1990s when it became a well-recognized activity. Researchers have established that when recycling fully satisfies the requirements of NA, it will develop the potential to ensure a lifetime existence of NA resources (Xuan et al., 2017). Currently, most countries in Europe include recycled concrete as part of the overall plan for aggregate resource management. The process of manufacturing RAC leads to the conversion of waste products into useful resources and minimizes the total amount of land used as disposal for demolition debris, hence, it is environmentally friendly (Andal et al., 2016). However, besides its environmental friendliness, the recycling process still creates dust, traffic, and noise which can be mitigated by recognizing all environmental concerns as early as possible.

The production process of RCA involves demolished concrete structures including abandoned roads, bridges, and buildings (Radević et al., 2017). In order to substitute NA, it is necessary to ensure that RCA meets the physical specifications which are required as the end product for use and the final prices should be fairly competitive. The physical properties of RCA and NA can be differentiated by observing the cement paste around the CC (Abdel-Hay, 2017). RCA material absorbs water rapidly compared to NA and the gravity in RCA is lower than in NA. This in turn heavily affects the utility of RAC in applications such as concrete and road base. Besides this, RAC has been applied in various industrial applications such as the production of concrete (Katkhuda and Shatarat, 2017).

RCA is significant in various construction areas such as road constructions, drainage structures, noise barriers, and pavement subbases (Yaowarat et al., 2019). In most cases, RCA are used in concrete as coarse aggregate and its production eventually leads to the production of a number of by-products. These materials can be used in compounds as ground improvement materials, concrete addition materials, and asphalt fillers (Ma et al., 2019). RCA also conserves the environment by minimizing the amount of CO_2 released into the atmosphere by absorbing it during the crushing process. The recycling process of RCA can drastically reduce the construction cost and increase employment opportunities in the recycling industries (Al-Bayati et al., 2018). Research has also established that RCA is safe to use and it reduces the number of virgin aggregates created, hence, leading to less use of the existing natural resources.

Clearly, high performance RAC is a special type of concrete prepared by RCA with high durability and strength beyond levels observed in other concretes produced through ordinary methods. For concrete to be classified as high performance, certain characteristics that are considered mostly depend on the characteristics of ordinary concrete which are largely achievable at a particular location and time (Aliabdo et al., 2018). Currently, the developed countries refer to high performance RAC as concrete with more than 28 days of compressive strength and over 50 MPa with a durability factor above 80% and less than 0.45 of water-to-cement ratio (w/c). Mostly, its high performance can be achieved through utilizing low w/c (about 0.25) and utilizing pozzolans which are useful due to their ability to produce a dense structure that has high strength and low permeability (Rattanachu et al., 2019). Interestingly, concrete structures that employ RCA have a similar level of durability as structures that employ NA if used as internal curing (IC) agent (Dimitriou et al., 2018). Efforts have been made to create various concrete products by RCA. This factor creates an opportunity for the reduction of waste in landfills and the mitigation of the depletion of natural resources.

2. Literature review and research hypothesis

This section of the model draws the knowledge on the cost-benefit analysis of RAC production from existing literature. There are various publications related to cost-benefit effects of the manufacturing of RAC. Wijayasundara et al. (2016) carried out a financial analysis and they came up with economic benefits of recycling concrete waste. Also, the study concludes that there are various drawbacks that arise due to the current activities of landfilling waste. These drawbacks include the emission of waste material into the environment, thus, creating an unsustainable environment. Abdel-Shafy and Mansour (2018) carried out a study on the opportunities for establishing recycling facilities and came up with the factors that affect the feasibility of this practice. These factors include the recycling cost in each unit, the profit, and the revenue charged. In addition, Ding et al. (2016) have introduced the system dynamics technique to assess the environmental and economic effects of recycling compared to C&D waste disposal. The same approach was used by Di Maria et al. (2018) to conduct a cost-benefit analysis of the options related to C&D waste management and the economic viability of establishing the options to the market. Al-Swaidani and Khwies (2018) have carried out a mix design optimization of RCA considering less CO_2 disposal and economic mix design by applying the crystallization technique and artificial neural networks as a probability method.

Unfortunately, few existing studies are applicable to the research approach used in this research on RCA cost-benefit analysis. However, Jadhav et al. (2019) have analyzed the operation costs of RMC plants in producing RAC by applying the activity based costing (ABC). Using this model, one can use the ABC approach to identify the relevant activities and assign the cost of different resources to the products based on the resources consumed by the product during the manufacturing process. Also, this approach estimates commences by gathering the data of all costs to cost centers and using the cost drivers to allocate costs to each product based on the activity level. The steps involved in this process consist of, firstly, establishing all the relevant activities, secondly, using cost center to organize the activities, thirdly, establishing the main categories related to expenses, fourthly, establishing cost drivers to assign the expenses to different activities and the activities to products, fifthly, introducing a dependence matrix on the expense activities as a means of relating the expenses to activities, sixthly, identifying the cost for the different activities, seventhly, introducing a dependence matrix on product activities as a means of relating the activities to different products, and finally, calculating the final cost for each product. Almeida and Cunha (2017) confirmed the necessity of the ABC approach for its application is costing the manufacturing set-up of RMC plants.

The research conducted by Kazaz et al. (2017) introduces an approach to identify the existing volatility in the RMC industry which is indicated by the people and plant turnover. They observe that demand fluctuations have led to plant shutdowns at rates of about 3% of all plant shutdowns. In addition, reports by Ratnayake and Samarakoon (2017) show facts about the current cost structure revolving around the RMC plants and the overall RMC manufacturing industry. Another report by Du and Lin (2018) shows that the raw materials used have costs accounting for up to 45% of the annual revenue in the industry in addition to the capital intensiveness observed in the industry. An assessment of the industry's labor component shows that salaries and payments to subcontractors amount to 11.3% in salaries and 5.1% in subcontract payments. Freight costs outward and inward represent only 15% of the total revenue in the industry whereas the depreciation represents 4.2%. According to Jordehi (2019), the utility inputs and operation expenses including water, diesel, electricity, and natural gas in businesses generally account for the remaining balance. Jin et al. (2017) proposed a model that would manage the C&D waste recycling, the demand for the products recycled, and the policy intervention that would encourage recycling. In addition, Wijayasundara et al. (2018) carried a feasibility study on the structural purposes of recycling C&D waste and concluded that the current cost of RCA is higher than the cost of NAC. However, their study mainly focuses on the properties of RCA and does not report on the details of processing RCA in a manufacturing set-up. Senaratne et al. (2016) have also conducted a cost-benefit analysis on the minimization of construction waste and concluded that reusing construction waste has an overall benefit.

It is important to understand the cost-benefit perspective of manufacturing RCA for use in construction activities since it gives an insight into the drivers to commercial production and use of RCA from an industrial perspective (Arredondo-Rea et al., 2019). Equally, it gives an overall understanding of the significant areas to focus on to improve the RCA manufacturing process and to make it financially viable. While researchers have analyzed the feasibility of various recycling operations to produce RCA and established the requirements to keep RCA costs as minimal as possible, the cost details of adopting RCA at the industrial level has not been addressed (Junak and Sicakova, 2017). Interestingly, this research conceptualizes and models the needed changes in high-performance RMC manufacturing and concrete waste recycling to produce industrial-scale RCA and assesses the financial impacts and the adoption costs. Regarding this, the paper intends to establish this by firstly, evaluating the proposed setup of manufacturing RCA as a CMC in the RMC manufacturing set up and to establish the processes and the infrastructure required (Khodair and Bommareddy, 2017). Secondly, constructing a financial model that can enable the assessment of the cost of manufacturing RCA and introduce a method to apply it to the current RMC manufacturing and concrete waste recycling (Lage et al., 2020). Thirdly, to estimate the cost of RAC and the rate of replacing NA. Fourthly, to analyze the sensitivity of critical parameters that affect the cost of RAC including the price of CC, the processing cost of CC, the distance between the RMC plant and the recycling facility, and the composition of RCA (Aslani et al., 2018). Finally, to conduct the probabilistic estimation that can assess the results that account for the uncertainty of the above-mentioned parameters.

In order to come up with an overall model, the assessment can be carried out in a case study comprising six industrial levels RMC manufacturing plants and two recycling plants which are used to calibrate the model. The changes in the RMC plant set up are assessed and the results are observed to favor RAC manufacturing which depends on RMC plant storage mechanism and aggregate feeding (Mohammed and Najim, 2020). Based on the results, the RMC plants in this study are then classified into two different types namely overhead bin (OB) and front-end loader plants (FEL). The OB plant utilizes aggregate bins for storage which are located either on the ground, underground, or above the ground in order to receive the material, store it, and use it in an automated process that weighs and feeds in different batches (Katkhuda and Shatarat, 2016). FEL plant receives the aggregates and stores them in ground-based compartments which are open (Medina et al., 2016). In this process, the front-end loader manually feeds the aggregates in batches directed to a weigh hopper in a process that is eventually automated. The current plants can be classified into the first two plants due to the simplicity of the process (Lu et al., 2019a,b). A review of OB plant suggests that they are mostly applied in cities due to their high production capacity. FEL plant, on the other hand, is applicable in regional and suburban areas due to their relatively low production capacity (Abdulmatin et al., 2017).

This research aims to modify a cost-benefit financial analysis model carried out by Wijayasundara et al. (2016) and to employ in the production of ready-mixed high-performance concrete made with RAC in Thailand. The model presented intends to establish a high performance RAC manufacturing set up which includes the RMC manufacturing process and waste concrete recycling process. Based on these two, a cost-benefit model is established to provide for the assessment of the cost-benefit feasibility of high performance RAC manufacturing and to reduce the price of high performance RAC when compared to NAC. In this case, the existing price of high performance RAC is analyzed for the mix variations including strength types namely 65, 62, 60, 58, 55 and 50 MPa, replacement compositions of high performance RAC, binder mix compositions (0, 20, 40, 60, 80 and 100 wt.%), and the variations in which the manufacturing environment of the RMC has. The binder composition scenarios (MCB) have two ways in which the binder content can be increased in the mix, a process conducted by increasing the content of cement (Vijayaraghavan et al., 2017).

3. Research design

The cost-benefit assessment suggests that there is sufficient demand for RAC as a concrete product. To produce RAC sufficiently and at lower prices, RMC manufacturing plants and equipment can play a significant role in this by incorporating a substantial amount of their resources to the production of RAC. However, it is difficult to account for the demand and supply factors and the resultant effects on the pricing of RAC (Yap et al., 2018). Also, this assessment acknowledges that certain economic considerations encourage sustainable recycling and industrial applications of recycled concrete products. The assessment concludes that the existing RCA manufacturing plant capacity cannot accommodate RCA as a CMC. Therefore, according to Xuan et al. (2016), the existing manufacturing plant infrastructure and processes need to be improved by customizing the build capacity to favor the manufacture of RCA in high quantities and to reduce the cost of manufacturing. Moreover, the changes to be considered for an ideal RMC manufacturing plant set-up highly depends on the given specifications under which the high-performance RAC concrete would be manufactured in. Due to the crucial needs for equipment and quality material in the manufacture of RAC, this would greatly lead to high budgeting costs in the construction of better RMC plant setups (Wang et al., 2016). The analysis of these setups is included in this model as two categories namely OB and FEL plants (FEL) as shown in Figure 1 (OB plant ((a.1) and (a.2)) and FEL plant ((b.1) and (b.2))). The basic framework of the model and the approach used in the integration can be replicated in industries and applied in a wider international context.

The research introduces an integrated framework in which a high-performance RAC manufacturing setup which includes waste concrete recycling operations is proposed. Based on the proposed setup, a financial model is also introduced in which one can assess the financial feasibility for the manufacture of RCA at deprived costs as compared to NAC (Al-Bayati et al., 2016). The price of high-performance RCA has been evaluated by assessing different variations of the mix including the mix compositions of the binder, strength types, and RCA replacement compositions. Figure 2 provides a financial breakdown of the different elements used in estimating the price of RCA. In addition, it provides details of the parameters used in the Eqs. (1), (2), (3), (4), (5), (6), (7), and (8). Also, Table 1 shows in the process elements and their indirect costs (Wijayasundara et al., 2016). Theoretically, a unit metric tonne of RCA can lead to an incremental cost. In this model, a product from an RMC manufacturing plant has been presented as $\mathbf{P_j}$ where $\mathbf{j}$ is the total number of products in the product range. The full RCA replacement composition is represented as $\mathbf{i}$ and $\mathbf{k}$ is the identity of the actual RMC plant whose data is being used. The categorization of the plant used is based on the feeding mechanisms on aggregate and t is a value representing a single

Figure 1. (a) Aggregate unloading to OB plant and (b) aggregate feeding in FEL plant.

type whereas $\mathbf{N_t}$ stands for the total number of plants in each category of **t**. In order to estimate the cost of materials and processing operations, the incremental approach has been used where the cost of manufacturing NAC has been used as the base of the study. According to (Mohammadinia et al., 2019), for each product $\mathbf{P_j}$, when RCA replacement occurs for each scenario **i** and the product is manufactured in plant type **t**, the product's unit incremental selling price is defined as in Eq. (1) (Wijayasundara et al., 2016):

$$\mathrm{UISP_{i,j,t} = PM + UIC_{i,j,t}} \tag{1}$$

In this case, **PM** represents the product's profit margin, $\mathbf{P_j}$ represents the product, and $\mathbf{UIC_{i,j,t}}$ represents the unit incremental selling cost of the product per cubic meter (m^3). In order to represent the PM value, the industry's profit margin is obtained by assuming the allocation of profit is based on a cost proportional basis for the overall product range (Sáez del Bosque et al., 2017). The product's unit incremental cost is represented as the sum of two different elements as shown in Eq. (2) (Wijayasundara et al., 2016):

$$\mathrm{UIC_{i,j,t} = UIMC_{i,j,t} + UIPC_{i,j,t}} \tag{2}$$

In this case, the two elements stand for the unit incremental material cost while the other stands for the RCA processing cost per cubic meter (m^3). Since the unit incremental material cost **(UIMC)** does not depend on the type of the RMC plant, in order to make the **UIMC** and **UIPC** application base similar, UIMC is calculated by taking into consideration the data set in each plant type and is defined as in Eq. (3) (Wijayasundara et al., 2016):

$$\mathrm{UIMCi,j,k} = \frac{\mathrm{IMC_{i,j,k}}}{\mathrm{QRAC_{i,j,k}}} \tag{3}$$

In this case, **QRAC** represents the quantity of RCA produced in a certain plant and is represented by the Eq. (4) (Wijayasundara et al., 2016):

$$\mathrm{QRAC_{i,j,k} = QRMC_{k,j} * CPRO_{k,j} * CRAC_{k,j}} \tag{4}$$

where **QRMC** is the RMC output quantity annually in the manufacturing setup, **CPRO** is the composition of the product $\mathbf{P_j}$ as a fraction of the overall production, and **CRAC** represents the RCA product composition of a certain product **j** in the overall RMC production.

The incremental material cost of RCA is slightly different to that of its rival NAC due to the variation in material prices and the mix composition. In this case, the incremental material cost of RCA is defined as in Eq. (5) (Wijayasundara et al., 2016):

$$\mathrm{IMC_{i,j,k} = MC_{i,j,k} - MC_{i=0,j,k}} \tag{5}$$

In this notation, the material cost of RCA production is presented as $\mathbf{MC_{i,j,k}}$ where RCA replacement takes place per **i** for each **j** in **k**. In Eq. (5), to approximate **IMC**, zero RCA replacement (where **i** = 0) is subtracted from each RCA replacement rate subsequently (Shi et al., 2019). The material cost is approximated by adding the component cost of raw materials for each product and is represented as in Eq. (6) (Wijayasundara et al., 2016):

$$\mathrm{MCi,j,k} = \sum_{\mathrm{i=1}}^{7} \left(\mathrm{PRM_{l,k} * QRM_{i,j,k}}\right) \tag{6}$$

In the above equation, **PRM** represents the cost of raw material (denoted as **l**) in a plant **k** and QRM represents the material quantity (denoted as **l**) for each product **j**. The main materials (denoted above as **l**) used in the manufacture of RCA are cement, slag, water, fly ash, coarse RCA, fine aggregate, and coarse NA. The discount for the purchase of these materials in higher quantities is assumed to be insignificant for individual materials, hence, the prices remain the same regardless of the quantity ordered. **PRM** has two major elements which are represented in the Eq. (7) (Wijayasundara et al., 2016):

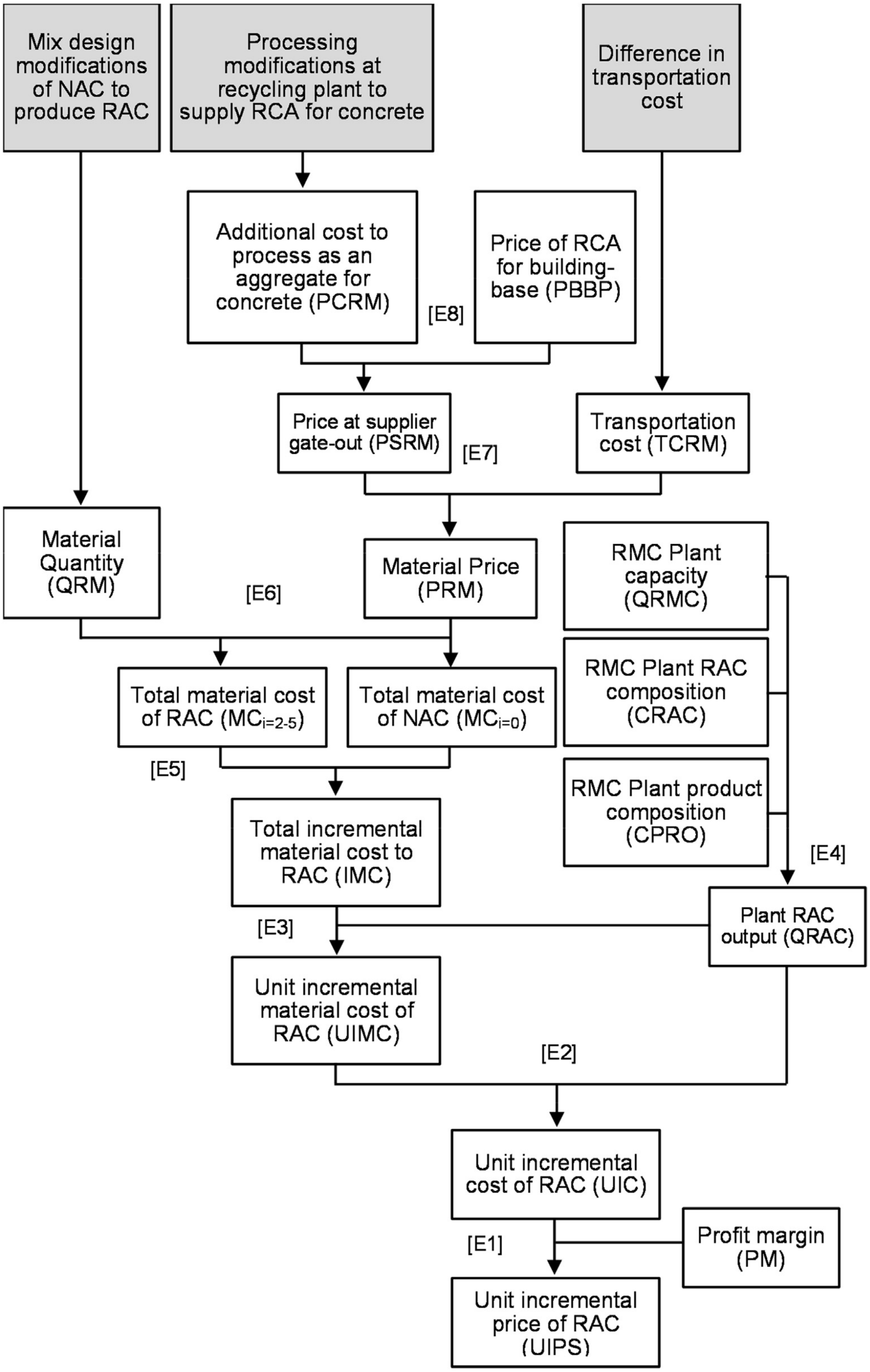

Figure 2. Estimation of RCA incremental price (Adapted from Wijayasundara et al., 2016). (With permission from Elsevier (Copyright © 2016 Elsevier)).

$$PRM_{l,k} = PSRM_{l,k} + TCRM_{l,k} \tag{7}$$

In this expression, **PSRM** stands for the price of the raw materials supplied while **TCRM** stands for the transportation cost of the material between the RMC plant and the pickup point. The **PSRM** in RCA production is given as in Eq. (8) (Wijayasundara et al., 2016):

$$PSRM_{l,k} = PRBP_{l,k} + PCRM_{l,k} \tag{8}$$

where **PRBP** stands for the road-based product price which is currently being manufactured at the recycler and **PCRM** stands for the materials' pre-processing cost to meet the required quality criteria.

Figure 3 represents the steps related to the ABC approach as adopted in this research to approximate **UIPC** in Eq. (2). Also, Tables 2, 3, 4, 5, and 6 represent RMC manufacturing plants, estimated preprocessing costs, first and second MCB mix compositions, product composition, and

Table 1. Process elements and their indirect cost (Wijayasundara et al., 2016).

Element Number	Element Description	Apportionment Basis
1	Management	RCA volume
2	Customer and logistic services	RCA trucks requested
3	Maintenance	RCA volume
4	Finance	RCA sales revenue
5	Procurement	RCA volume
6	Quality control	RCA volume
7	Information technology (IT)	RCA sales revenue
8	New projects and upgrades	RCA volume
9	Administration and utilities	RCA volume

the impact of manufacturing process respectively. To begin with, the accounting information sources on finance and management are analyzed to draw the NAC manufacturing costs (Bartolacci et al., 2018). Table 2 represents the RMC manufacturing plants alongside concrete waste recycling and shows the actual input for each type of plant in m^3. Table 3, on the other hand, shows the approximation of preprocessing costs for each plant and the amount of hours used. Also, Table 4 shows the mix compositions of first MCB and second MCB using the RCA strength and the RCA replacement. The incremental cost estimates for each plant setup are, then, established based on the RCA processing requirements. Finally, a special cost model is used to collect the costs to cost centers in a process represented by indirect or direct cost elements (Paul et al., 2018). The indirect costs refer to support cost commonly known as overheads while direct costs are the costs directly attributed to the RCA production. Based on factors such as floor area and process output, overheads need a separate allocation base where according to ABC principles, the allocation base is used in the distribution of indirect costs (Guo et al., 2018). This happens on a proportion base to different processes that are relevant based on the consumption of resources. According to (Salesa et al., 2017), during the production process, the allocated costs are collected, combined, and allocated to the product based on the level of process activity for each product.

4. Results and robustness analysis

Based on the results obtained from the research approach, various results were obtained including how the incremental material cost is affected by the cost of RCA, the incremental processing cost, and RCA's unit incremental cost. Based on the research approach, the average cost of RCA after additional quality control and pre-processing to produce structural concrete is higher than the cost of NA (Sadati et al., 2016). Figure 4 shows the estimated breakdown of the cost of RCA. More than half of this cost is as a result of the additional quality control and pre-processing cost. If the industrial production of RAC takes place, the cost of pre-processing could decrease due to the modification of the

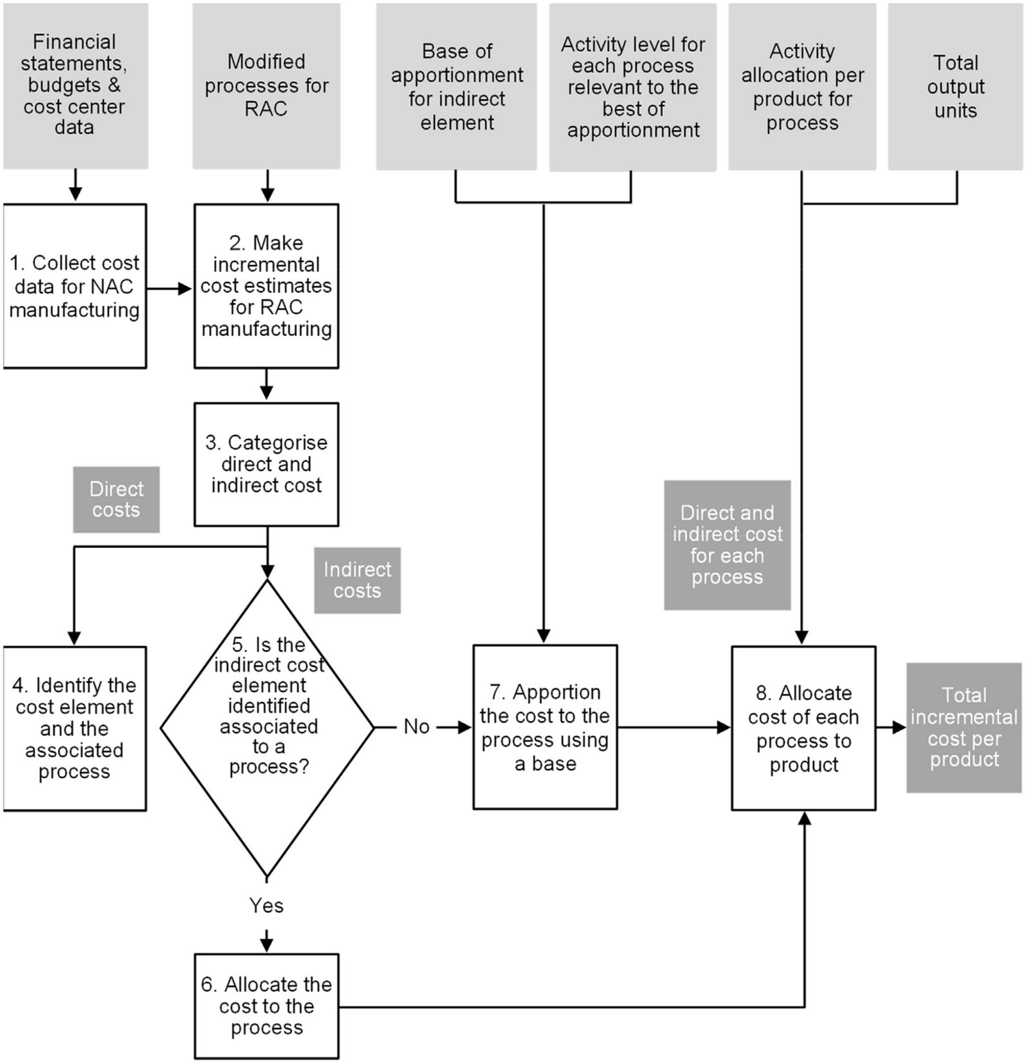

Figure 3. Steps in the ABC approach (Adapted from Wijayasundara et al., 2016). (With permission from Elsevier (Copyright © 2016 Elsevier)).

Table 2. RMC manufacturing plants.

Plant number	Category	Operator number	Annual output in m^3	Type
1	RMC	3	150,000	Recycling plant
2	RMC	2	45,000	Recycling plant
3	RMC	1	85,000	FEL
4	RMC	2	30,000	FEL
5	RMC	1	80,000	FEL
6	RMC	2	100,000	OB
7	RMC	1	150,000	OB
8	RMC	2	180,000	OB

Table 3. Estimation of preprocessing costs.

Plant number	Unit	Description	Amount
7	Hour	Operational hours for handling additional materials	10
7	USD per hour	Cost of material handling labor	55
7	USD or MT	Number of days operated	275
7 and 8	Hour	Hours of quality control for each 1000 MT of product	6
7 and 8	USD per hour	Hours of quality control for each 1000 MT of product	50
7 and 8	USD per month	Extra cost of testing	950
8	USD	Scrap value	0
8	Years	Useful life	40
8	%	Coarse RCA yielded from crushed concrete	75
8	%	Utilization of the premises manufacturing crushed concrete	65
8	MT per hour	Hourly capacity depending on upgrade	120
8	USD	Upgrade cost	550,000
8	USD or MT	Additional screening cost	5

Table 4. Mix compositions of first and second MCB_1 and MCB_2.

Mix number:	-	1	2	3	4	5	6	7	8	9	10	11	12
RCA replacement (% wt.):	-	0	0	20	20	40	40	60	60	80	80	100	100
RCA strength (MPa)	-	65	65	62	62	60	60	58	58	55	55	50	50
First MCB MCB_1	Type 1 Cement (kg/m^3)	665	665	630	630	605	605	582	582	545	545	500	500
	Water (kg/m^3)	125	125	125	125	125	125	125	125	125	125	125	125
	FA (kg/m^3)	818	770	834	783	842	793	852	802	867	816	885	833
	NA (kg/m^3)	851	840	694	694	525	557	356	376	181	191	0	0
	RCA (kg/m^3)	0	0	173	173	350	376	534	564	724	766	925	978
	Silica fume (kg/m^3)	0	0	0	0	0	0	0	0	0	0	0	0
	Superplasticizer (liters/m^3)	7.1	7.1	6.6	6.6	6.4	6.4	6.2	6.2	5.8	5.8	5.0	5.0
Second MCB MCB_2	Type 1 Cement (kg/m^3)	603	603	563	575	545	553	527	539	497	507	458	465
	Water (kg/m^3)	125	125	125	125	125	125	125	125	125	125	125	125
	FA (kg/m^3)	809	786	830	801	832	795	871	802	879	827	885	833
	NA (kg/m^3)	839	856	702	716	530	565	359	376	183	193	0	0
	RCA (kg/m^3)	0	0	176	179	356	374	538	564	732	772	925	978
	Silica fume (kg/m^3)	71	62	67	55	60	52	55	43	48	38	42	35
	Superplasticizer (liters/m^3)	7.3	7.2	7.0	6.8	6.7	6.6	6.5	6.3	6.1	5.9	5.3	5.1

Table 5. Product composition.

Plant number	Category	Product strength (MPa)					
		50	55	58	60	62	65
1	OB	10	55	40	15	15	10
2	OB	40	45	20	15	10	5
3	Front-end	60	30	15	5	0	0
4	Front-end	30	30	20	5	15	5
5	Front-end	35	30	20	5	15	5

Table 6. Impacted processes as a result of the manufacturing.

No.	Process	Dir1	Dir2	Dir3	Ind1	Ind2	Ind3	Ind4	Ind5	Ind6	Ind7	Ind8	Ind9
1	RCA receipt												
2	Quality control		*	*			*		*				*
3	Storage conveyance			*			*		*				*
4	Storage		*	*			*						
5	Mixing conveyance		*										
6	Dry mixing												
7	Wet mixing			*									
8	Transportation												
9	Unloading												
10	Truck return												

recycling plants which can supply high-performance concrete directly. However, the selling price of FRCA would affect the recycling cost since the financial feasibility of RCA as a CMC would largely depend on establishing a sustainable FRCA end-use (Zhou and Chen, 2017). Interestingly, the increased purchase price of RCA signifies that the refinement level is higher. Also, the higher the pre-processing cost or purchase price, the more the similarity between the properties of RCA and NA, hence, the lower the modifications needed in the design of the mix (Hou et al., 2017). Therefore, is it worthy to investigate the cost of refining RCA and the extra cost of materials needed as a result of the modified design of the mixtures. Concrete demolition waste (CDW) can be practically handled by crushing CC to produce RCA and recycling it with NA to produce concrete elements. For many years, pavements created from demolished concrete have been used in road base course as a stabilizing component. With the relevant sorting, it is practicable to use RCA as an additional raw material in the production of various concrete elements.

Tables 7 and 8 show the estimated preprocessing incremental cost and the estimated cost of processing in OB and FEL plants according to the ABS approach respectively. The cost of processing can be fixed, variable, and semi-variable, a factor that indicates the degree of increase which varies with the increase in RCA replacement (Pickel et al., 2017). The main processes affected by the manufacture of RCA are the storage of RCA, storage conveyance, RCA quality control, and wet mixing of concrete. With the breakdown of PM, UIMC, and UIPC for OB and FEL plants, the RCA's incremental selling price, abbreviated as UISP, is represented in Figures 5 and 6 for different MCB scenarios. According to the figures, the cost of RAC increases when manufactured in OB plants and decreases when produced in FEL plants. The increase in UIC in RAC produced by OB plants is mainly caused by the increase in the estimated UIPC. In OB plants, the proportion UIC varies from 52% to 72% to that of UIPC whereas, in FEL plants, it varies from 32% to 41% (Teh et al., 2018). According to the figures, it is clear that the increase in RCA replacement is mainly as a result of the increase in UIMC. Also, the IMC is higher when the MCB_1 in the first scenario is adopted as compared to the MCB_2 in the second scenario. The incremental cement addition in the first scenario increases with the RCA replacement rate whereas the second scenario cement replacement content increases with the increase in RCA replacement rate (Garcia et al., 2017). Therefore, this difference appears as a result of the increase in cement content and this raw material is regarded to be one of the most expensive materials in the mix. An evaluation on the mechanical properties of concrete with various portions of RCA reveals that there is minimal workability effect and 10% reduction in the strength of compression. Therefore, industrial-scale manufacture of RCA will positively impact the concrete recycling and production industry. The cost of the industrial manufacturing process can be reduced by using advanced sorting processes for both the recycled concrete and the additional recycled products. The sorting process can ensure production of high quality concrete compared to NAC with lower production cost. The process ensures the proportions of the products are evaluated and the proportions are used in the right quantity for a proper end product.

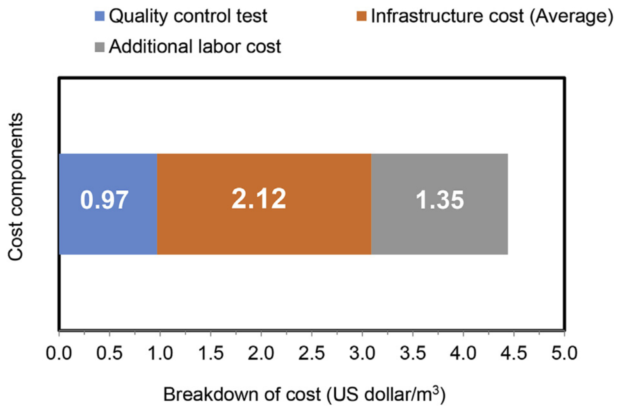

Figure 4. Increase in RCA cost.

Due to the expected uncertainty with the main variables used in the model, a sensitivity analysis is conducted by taking into account the key parameters. The objective of this analysis is to establish the effect of the main variables to a change in a single unit of the output. The key parameters considered are the composition of RCA, the additional cement required to manufacture RCA, the additional preprocessing cost of RCA, and the transportation distance (Oliveira Neto et al., 2017). According to Oliveira Neto et al. (2019), crushed demolition concrete with depleted NA is generated in huge amounts and it should be utilized cost-effectively and in an ecofriendly manner. Since the parameters have characteristics of a normal distribution, the deterministic value is identified as the mean and the input variable range can be evaluated to find the lower and upper bound. Table 9 shows the standard deviation and the mean, where the mean is a sixth of the margin. Also, Table 10 shows the incremental price range of RCA obtained by dividing the change in the products' cost by the change in quantity. To ascertain the impact of the final price of the output as a result of the key input variables' uncertainty, the possible range of the price of RCA has been approximated using Monte Carlo simulation (Park et al., 2019). The final observation is that regardless of the type of manufacturing plant, the possibility that the cost of RCA is below that of NAC is next to zero. Furthermore, RCA products manufactured in OB plants have higher incremental prices compared to FEL plants (Amrutha Balan and Abin Thomas, 2019). The most applicable price of RAC was not affected by the different scenarios of MCB. Also, RCA has impressive properties that are maintained and which yield higher mechanical properties than NA. Using RCA in the high performance concrete can produce optimal performance considering the economic, technical, and environmental effects.

To render the testing robust, different mixtures with water and variations of superplasticizer are used as test judges. Properties to be tested are workability parameters, mechanical properties, and various rheological properties. The robustness of the different mixtures containing

Table 7. Approximating the processing incremental cost.

Plant No.	Process	Dir	Ind	Description	Unit	Amount
1	4	3	3	Cost of maintenance	USD per year	2500
2	3	3		Consumption of diesel	1 per year	2000
3	4		9	Cost of constructing storage bin	USD	60,000
4	7	3		Mixer power	Watts	427

Table 8. UIPC for FEL and OB plants.

Plant type	FEL						OB					
RCA replacement	0%	20%	40%	60%	80%	100%	0%	20%	40%	60%	80%	100%
(Process) 1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0.48	0.53	0.64	0.69	0.73	0	0.23	0.29	0.33	0.37	0.44
3	0	0.06	0.06	0.07	0.07	0.08	0	6.05	6.12	6.29	6.31	6.37
4	0	0.07	0.21	0.25	0.29	0.33	0	0.05	0.07	0.15	0.18	0.21
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0.12	0.13	0.13	0.13		0.12	0.13	0.12	0.13	0.13	0.13
8	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
(Process) 10	0	0	0	0	0	0	0	0	0	0	0	0

cement variations is tested for 21 properties which are described as the 'judges'. The test results in coefficient of variation (COV) values which are discovered from each property tests and the ranking that corresponds to each mix. If a certain property value fails to appear, then, it is impossible to establish the test which can measure it as a result of self-compatibility destruction. This mix is ultimately ranked as the one with the highest value. The mix that records the lowest value of COV in the mix holds the highest level of robustness (Taboada et al., 2018). All properties must be evaluated to obtain the level of robustness and for each mix, the individual rankings are summed up to obtain the 'SRi' value. This value is used to rank the concrete mixtures containing different material variations based on the level of robustness. According to the sum of ranking, a category is generated to classify the robustness selected as either low, medium-low, medium-high, or high.

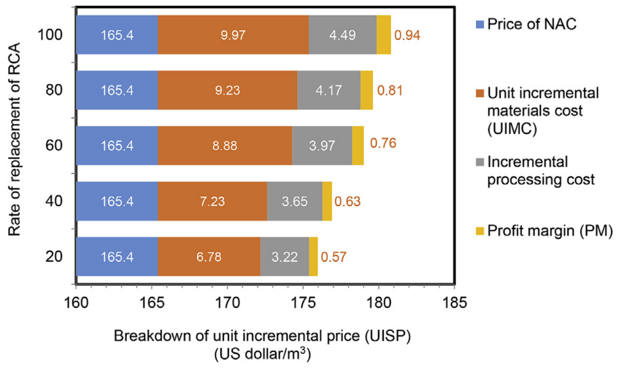

Figure 5. Breakdown of unit incremental price in FEL type plant for 60 MPa using MCB_2 scenario.

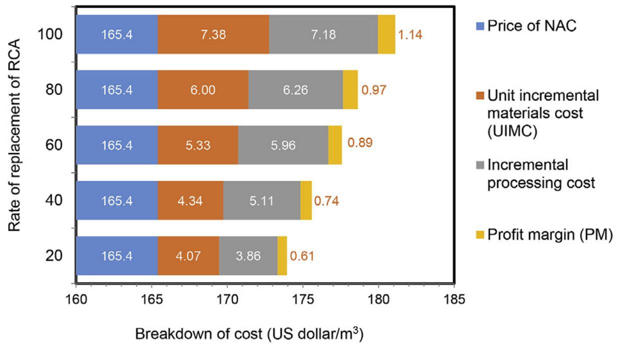

Figure 6. Breakdown of unit incremental price in OB type plant for 60 MPa using MCB_2 scenario.

5. Discussion

The use of high levels of recycled aggregates has been identified to negatively affect the properties of concrete. According to Li et al. (2016), the compressive strength and elastic static modulus decrease with the increase in the content of the recycled aggregate. However, the use of a lower w/b ratio can adequately compensate for the reduction. In addition, the addition of cement in the recycled aggregate at the same w/b and replacement ration decreases the compressive strength and tensile splitting strength (Ozbakkaloglu et al., 2018). However, partial usage of fly ash as a replacement for cement reduces the shrinkage of RAC. Fly ash leads to the greater long-term durability of the recycled aggregate concrete due to the pozzolanic reaction of fly ash.

To calculate the cost and benefit of recycling concrete, it is important to note the amount saved in recycling. Additionally, an additional amount is saved since no there is no dumping and no production of new materials. A summary of the detailed cost data for the current concrete recycling process method can be accessed in a report released by the Environmental Protection Agency (EPA) in 2007 (EPA, 2007). However, some crucial cost data is still unavailable. In order to establish this, the agency needs to conduct in-depth discussions with representatives from different demolition and construction companies in order to establish the environmental and social costs of using recycled aggregate in comparison to conventional concrete. To establish the cost of using recycled concrete aggregate against conventional concrete, we analyze conventional concrete methods. In the conventional method, construction waste should be considered for analysis in the first stage of the cost analysis. Construction waste is used in the first stage of construction where it is sent to landfills for disposal, and hence, the cost is incurred in form of landfill charge, transportation charge, landfill space, gas emission, air pollution, noise pollution, and energy consumption.

Table 9. The key parameter's standard deviation and mean.

Parameter	Units	MCB first scenario		MCB second scenario	
		Mean	Standard deviation	Mean	Standard deviation
Content of supplementary cement	kg/m^3	415	81	380	66
Composition of RCA	%	65	0.3	55	0.4
Distance to transport RCA	kilometers	32.4	6.2	40.5	5.3
RCA additional processing cost	USD per MT	4.3	0.2	3.9	0.5
Inward bound CC price	USD per MT	36.9	4.4	25.8	3.7

The second stage involves stripping where the rocks are leveled and cleared using equipment such as bulldozers. Costs incurred in this stage include fuel cost, labor cost, and overhead cost. The third stage is the blasting process where blasting machinery is used. The costs in this stage include capital cost, working capital cost, cost of machinery, fuel cost, fixed overhead cost, and labor cost. The fourth stage, stockpiling, involves labor cost at an estimated rate of $18/h. Sorting is the fifth stage where equipment is allocated, including excavators, and involves costs such as capital, working capital, operating, fuel, fixed over-head, labor, equipment, and equipment maintenance cost. The crushing process is the sixth process which involves magnetic separation, primary crushing, and secondary crushing. Equipment used includes the shaper, secondary crusher, and primary crusher. In addition, capital cost, labor cost, fixed overhead cost, fuel cost, and equipment maintenance cost have to be considered. In this process, the only benefit incurred is maintenance cost which is easily saved compared to the recycling process due to the wear and tear of the machinery blades used. The sixth stage involves the screening, washing, and air sitting process which involves recycled water and fuel to settle the dust and other particles down. Finally, the product stage involves finished products of different millimeters sold at different prices from $15 to $25.

The conventional cost is very high compared to the recycling method where construction waste is used in recycling plants to produce new products. The first stage of the recycling process involves the construction waste which is dumped in the recycling plants at a low dumping charge. Additional charges include transportation and energy consumption charges. The second stage involves stockpiling where single labor is used at a rate of $18/h. The third stage involves sorting where machinery such as excavators and pulverisers are used. Additional capital, equipment, operating, working capital, fixed overhead, fuel, labor, and equipment maintenance costs are also charged. In the fourth stage, the crushing process, includes primary crushing, secondary crushing, and magnetic separation. It involves capital, working capital, operating cost, fixed overhead, and fuel costs. Also, this process involves the sorting of steel scrap through magnetic separation and is sold at about $100/tonne. The fifth stage involves the manual removal process where pieces of wood, plastics, and paper are removed from the crushed materials. The labor involved in this process is charged at a rate of about $18/h. The sixth stage involves screening, washing, and air-sitting which is similar to the conventional method. In this stage, recycled water and fuel are used to settle the dust particles. The final stage of the recycling process involves finished products which are sold at prices ranging from $14 to $22 dollars.

Table 10. RCA incremental price range.

RCA replacement (%)	FEL	OB
20	0 to 7.5	5.5 to 16.0
40	7.5 to 9.5	7.5 to 16.5
60	8.5 to 10.5	9.5 to 17.5
80	4.5 to 12.5	9.5 to 18.0
100	5.5 to 12.0	9.0 to 18.0

Therefore, recycled aggregate concrete has more cost-benefits than conventional methods. According to Tam and Tam (2007), the recycling process receives an annual net benefit of about $30,916,000 while the conventional methods receive a negative net benefit estimated at -$44, 076,000. The economic benefit of recycling concrete leads to more long-term advantages than using natural aggregate.

6. Conclusions and recommendations

The paper establishes a cost-benefit analysis framework concerning the feasibility of manufacturing RCA for high performance RAC production. Clearly, for financial viability in the manufacture of RCA, RMC manufacturing plants can be used to obtain industrial-scale products. The financial impact is evaluated based on an incremental basis, where the operation case is considered to have zero incremental cost. The base operation case considers recycling concrete waste in manufacturing RMC plant as building and infrastructural materials. The model developed is drawn from data obtained by various manufacturing plants and concrete recycling plants which are used as case studies to approximate the unit incremental selling price. FEL and OB types of plants are the best RMC manufacturing plants to be used due to their aggregate mechanism of feeding. The current problem experienced in Thailand where a lot of concrete waste is being disposed of from the demolition plans and unsustainable concrete is being used will be solved using RCA manufacturing. The conclusions and recommendations are summarized as follows:

- The increase in RCA replacement is mainly as a result of the increase in unit incremental material cost (UIMC). Moreover, the incremental cement addition in the first scenario (65 MPa compressive strength and 655 kg/m^3 of Type 1 cement) increases with the RCA replacement rate whereas the second scenario (65 MPa compressive strength and 603 kg/m^3 of Type 1 cement) cement replacement content increases with the increase in RCA replacement rate.
- Estimated breakdown of the cost of RCA as a result of the additional quality control and pre-processing cost. However, the cost of preprocessing could be decreased by modifying the plants to high-performance concrete directly.
- The cost of RAC increases when manufactured in overhead bin plant (OB) plants and decreases when produced in Front-end loader plants FEL plant. The increase in the unit incremental selling cost (UIC) in RAC produced by OB plants is mainly caused by the increase in the estimated UIPC.
- The assumption that using RMC manufacturing plants to produce RCA as a CMC could have extreme incremental costs due to the specific plant conditions. Also, it is difficult to introduce FRCA during the implementation of RMC manufacturing plants in the manufacture of RCA. To improve RCA production, nanotechnology can be applied due to its great potential for enhancing the manufacture and quality of RCA in high performance RAC production. Further the application of nanotechnology concentrates on the modification of RCA using nanomaterials. The technology characterizes the different properties of RCA at a nanoscale level using various advanced instruments. Therefore, it is recommendable to focus on nanoscience research

which is important in the study of the microstructure of RCA. Also, the mechanical properties of RCA can be improved using nanomaterials to achieve higher strength as compared to NAC.

- The addition of high-performance pozzolans to the recycled aggregate concrete as a way of improving its performance can increase the cost of using RCA. However, a cost-benefit analysis of the addition of fly ash shows that it is worthy due to the increase in durability. Low concrete quality is one of the burdens associated with the use of recycled materials.
- To encourage the use of RCA, the government should initiate the use of RCA in their projects. The cost of the use of RCA can be lowered by the integration of advanced technology in the production process to improve quality. These technologies can be implemented through government and client funds in addition to incentives that can support the process. To facilitate this move, in-house training programs should be implemented for all employees to enhance the process which will, in turn, enhance environmental awareness.

Declarations

Author contribution statement

Natt Makul: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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