Evaluating the Carbon Neutrality of Concrete Recycling Using CO_2 Capture Technologies from Cement Production

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Abstract -

The construction industry encounters significant environmental challenges, primarily due to concrete waste from demolitions and high CO_2 emissions from cement production. Concrete waste is recycled into aggregates, generating a significant amount of waste concrete powder (WCP) as a byproduct. However, the application of WCP in recycling processes is limited, leading to landfill disposal and environmental risks. This study explores the potential of combining carbon-neutral technology with large-scale concrete production by using WCP as a partial substitute for both cement and fine aggregates. Active carbonation is highlighted for its ability to capture CO_2 while improving the properties of recycled concrete aggregates (RCA) and WCP. Although technological advancements exist, a thorough evaluation of financial viability is essential. This research focuses on assessing the economic feasibility of integrating carbon-neutral technology into concrete recycling, particularly by carbonating waste concrete using flue CO_2 from cement plants. Thus, the paper proposes a method to incorporate environmental assessments into an activity-based costing (ABC) model, enabling a dual evaluation of financial costs and environmental impacts. By linking environmental impact assessment results to costs, this approach facilitates a comprehensive evaluation for involved stakeholders. An assessment of the Hong Kong market showcases the practicality of the proposed matrices. The comparison of recycling methods indicates significant environmental improvements, with 362% and 440% reductions in CO_2 emissions from cement plants and natural material processing, respectively, underscoring the potential of carbonization technology and the need for government support.

Keywords -

Construction waste management, Concrete recycling, Flue gas, CO_2 sequestration, Recycled concrete aggregate

1 Introduction

The construction sector stands as a foundational component of the economic system, notable for its substantial energy usage and considerable carbon footprint. It has been documented that approximately one-third of worldwide carbon emissions can be attributed to the construction sector. Importantly, the adoption of recycled materials has been recognized as a powerful strategy to cut down on carbon emissions within this industry. Over fifty percent of construction and demolition debris is comprised of materials like waste concrete, as well as fractured bricks and blocks. These materials hold significant promise for lowering carbon emissions through recycling and reuse [1]. Research by Xiao, et al. [2] indicates that using recycled concrete has the potential to reduce carbon emissions by 12.4-52.2%, a percentage that is likely to grow in tandem with the escalation in recycled material usage. Furthermore, the employment of recycled concrete can help to mitigate the global scarcity of raw materials, like sand and aggregates. The adoption level of recycled concrete now serves as a critical measure within the green building evaluation frameworks of various countries.

While the advantages of waste concrete are widely recognized, the actual rates of recycling in numerous regions, including Hong Kong, still remain a concern for stakeholders. Waste concrete can be processed into recycled concrete aggregate (RCA), suitable for use in fresh concrete mixes. This recycling also leads to the creation of waste concrete powder (WCP), which can constitute 30-70% of the utilized concrete [3]. In countries such as China, the yearly output of WCP from recycling activities is estimated to be a staggering 60 million tonnes [4]. Instead of the prevalent method of landfill disposal, WCP could be used as a partial replacement for cement in concrete mixes. This substitution can lower the usage of cement-based materials, improve the rheological and mechanical characteristics of the concrete, and increase its durability.

Thus, incorporating WCP into the recycling process can further improve the recycling rate and sustainability.

Given the considerable promise of waste concrete, a multitude of research has been conducted in recent years. These studies have primarily concentrated on enhancing the attributes of recycled concrete through technical means. For instance, Poon and Chan [5] explored the properties of recycled concrete when applied to concrete pavement, offering various recommendations for enhancement. A method employed to improve the strength and quality of construction materials sourced from waste concrete is carbonation, which also supports strategies aimed at achieving carbon neutrality [6]. Carbonation refers to the reaction between carbon dioxide in the atmosphere and the calcium hydroxide present in cement paste. To achieve concrete carbonation, a high concentration of pure CO_2 gas (up to 99%) is typically employed [7]. As indicated by Ouyang, et al. [8], carbonation curing can enhance the compressive strength of RCA by 13%. Furthermore, carbonation enhances the material's resistance to corrosion and frost, thereby prolonging its lifespan [9]. The carbonation of RCA not only enhances their properties but also helps reduce the greenhouse effect caused by carbon dioxide emissions [10]. WCP, owing to its inferior physical and mechanical properties, is not suitable for direct incorporation into concrete mixes, and similarly, RCA requires a pre-carbonization procedure. Recent studies have demonstrated the promising potential of carbonizing WCP in terms of enhancing the strength of future concrete and its viability as a material for carbon sequestration [11]. Liu, et al. [12] and Wu, et al. [13] research indicates that WCP can absorb CO_2 up to 21% of its own weight.

Recently, anthropogenic gases, such as flue CO_2 from cement plants, have emerged as a promising source for concrete carbonation. Studies have demonstrated the feasibility of sequestering CO_2 from flue gases into materials like air pollution control residues, capturing 8–12% CO_2 by weight [14], while improving concrete properties such as compressive strength [15]. Research has also highlighted the cost-effectiveness and carbon reduction potential of integrating CO_2 capture in concrete production [16]. Pilot projects worldwide, such as those in Canada and the U.S., have validated large-scale mineral carbonation and technologies like Reversa, demonstrating their readiness for commercialization and compliance with industry standards [17, 18].

The carbonation of waste concrete for CO_2 sequestration not only supports carbon neutrality goals but also improves the strength of construction materials derived from such waste. While projects utilizing flue gases for CO_2 sequestration show promise, reliance on commercially captured CO_2 remains a drawback, potentially conflicting with sustainable processing. Additionally, the lack of economic analysis limits the understanding of its cost-effectiveness. Additionally, the integration of WCP into the concrete waste recycling process has yet to be fully explored, despite research suggesting that WCP can substitute for cement and natural fine aggregates in concrete formulations [19]. In response to these challenges, this study investigates the feasibility and environmental impact of active carbonation techniques for RCA and WCP derived from concrete debris, aiming to incorporate them into non-structural concrete mixtures. It also assesses the feasibility of using alternative CO_2 sources, such as flue gases from cement plants, to sustainably process concrete waste and incorporate both elements into the recycling process.

2 Model development

The research methodology comprises four key steps. First, a comprehensive literature review was conducted, providing insights into construction and demolition waste (CDW) management, the carbonization of demolished concrete, and the integration of this technology. Second, a cost estimation matrix was developed to evaluate financial costs and environmental impacts, with parameters selected based on the relevant processes involved. Third, a case study focused on the Hong Kong market was chosen to assess the feasibility of the proposed process with carbon-neutral technology integration, comparing it to traditional methods. Finally, the parameters were entered into a simulation environment to evaluate the model's practicality and analyze the individual cost components.

2.1 Parameters selection

In Hong Kong's traditional waste management system, all concrete wastes are first processed through crushing and separation before being sent to recycling facilities for conversion into RCA [20]. The RCA is then delivered to concrete production plants, while any excess WCP generated during the refinement of demolished concrete is disposed of in landfills [21]. Natural materials such as sand, gravel, and cement are sourced from approved suppliers to prepare the final concrete product. The emphasis on recycling WCP and utilizing flue CO_2 from cement plants has prompted the exploration of an alternative supply chain for concrete recycling. In this approach, demolished concrete from construction sites is transported to the recycling facility for processing into RCA and WCP. Flue CO_2 serves as an alternative gas source for carbonization and is transferred from the cement plant to the recycling plant. The carbonized RCA and WCP are subsequently sent to the concrete plant. Additionally, natural materials (sand, gravel) and cement are sourced from designated suppliers, though the quantity of these materials is reduced due to their partial substitution with recycled aggregates and WCP. The processes discussed are illustrated in Figure 1, where black and blue arrows represent the traditional methods, while orange arrows indicate the proposed processes.

The activities carried out at various locations—such as suppliers, recycling facilities, cement plants, and landfills—are referred to as facility-based activities, with the associated expenses known as facility-based costs [22]. To achieve an accurate evaluation of all costs, an Activity-Based Costing (ABC) approach is utilized to allocate resources effectively to each process within a specific facility [23]. The energy (E) required for equipment operations at each facility and technology-related costs (AT) are quantified. The technology-related costs include expenses for acquiring additional equipment necessary for new concrete waste recycling processes. This encompasses equipment for capturing flue CO_2 and the enhanced capacity needed for carbonizing RCA and WCP. Additionally, the avoided effects are considered from an environmental perspective. Processes in the alternative scenario that replicate those in the traditional scenario are excluded from the model, as their impacts would remain consistent in both cases.

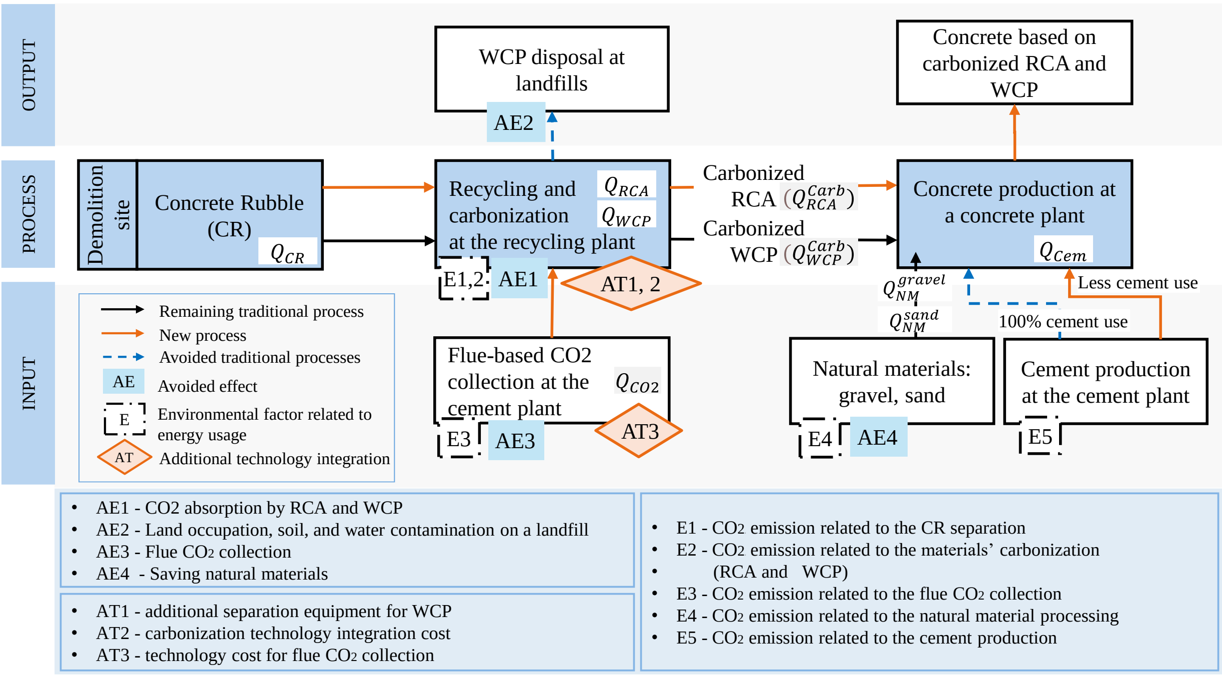

Figure 1. Identification parameters for the traditional and alternative concrete waste recycling processes

2.2 Model assumptions

The model assumes a one-way material flow, moving from demolition sites and suppliers to landfills or recycling centers, and ultimately to concrete plants, reflecting typical industry practices. No limits are imposed on the number of facilities at each stage to ensure scalability. All demolished concrete rubble (CR) delivered to recycling facilities is assumed to be fully processed into RCA or WCP, based on the efficiency of modern recycling technologies. Technology costs, reflected as depreciation, are based on initial purchase and installation expenses and are limited to equipment essential to the recycling process. Environmental benefits, including resource conservation and CO_2 emission reductions, are included to capture the sustainability advantages of substituting cement and natural aggregates with recycled materials. These assumptions are grounded in established practices and the specific context of this study.

2.3 Quantification of parameters

The quantification of parameters begins with the identification of activities within each facility and material flow based on Figure 1. The following material flow and related major facility-based activities can be determined:

a_1: Concrete rubble (CR) processing
a_2: RA processing
a_3: WCP processing
a_4: Anthropogenic CO_2 processing
a_5: Cement production
a_6: Natural materials processing (gravel)

a_7: Natural materials processing (sand)

For each type of activity, resources known as "activity drivers" will be allocated. An activity driver enables the allocation of economic transaction costs to an activity [24]. For instance, when processing concrete rubble (CR, represented as a_1) into RCA and WCP at a recycling facility, the resources utilized include the operational time of sieving and screening machines, as well as the energy consumed per unit of material processed. These resources can be represented as b_1 and b_2 respectively:

b_1: Usage of equipment (hours) per unit of processed material for CR processing into RCA and WCP (sieving and screening machines)

b_2: Energy usage (kWh) of equipment per unit of processed material for CR processing into RCA and WCP (sieving and screening machines)

b_3: Usage (hours) of carbonization equipment per unit of processed material for RCA and WCP carbonization

b_4: Energy usage (kWh) of carbonization equipment per unit of processed material for RCA and WCP carbonization

b_5: Usage (hours) of CO_2 collection equipment per unit of processed material at the cement plant

b_6: Energy usage (kWh) of CO_2 collect equipment per unit of processed material at the cement plant

Environmental parameters were calculated using life cycle assessment (LCA) to evaluate the sustainability of the proposed materials and processes. An extensive LCA was performed following ISO 14040 and 14044 standards using OpenLCA 2.0.3 software. The Ecoinvent 3.9.1 database was utilized for the assessment due to its reliable and compliant data source. The environmental parameters were determined by considering the electricity required for processing recycled aggregates before their inclusion in the production cycle. Additionally, environmental parameters were calculated for the production of natural aggregates and cement. To ensure consistency and comparability, transportation was not included in the boundary conditions for CO_2 emission assessment. By focusing on the direct energy and material inputs, the study isolates the specific contributions of transformation, providing a clearer insight into the sustainability potential of recycled aggregates.

To create a comprehensive representation, resources can be allocated to each activity and illustrated as a matrix (Eq. 1). In this matrix, the horizontal rows represent the various activities (e.g., CR, RCA, WCP, CO_2 processing), while the vertical columns correspond to the types of resources utilized (e.g., energy, depreciation costs). For instance, 'b_{11}' denotes the equipment usage time for processing one unit of CR, while 'b_{12}' represents the energy consumption of the separation equipment for processing one unit of CR.

$$B = \begin{matrix} CR \\ RCA \\ \vdots \\ NM_{sand} \end{matrix} \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{16} \\ b_{21} & b_{22} & \cdots & b_{26} \\ \vdots & \vdots & \ddots & \vdots \\ b_{71} & b_{72} & \cdots & b_{76} \end{pmatrix} \tag{1}$$

The costs of activity drivers (per unit) can be represented as a column vector (Eq. 2). For example, the unit costs of activity drivers $b_1 - b_6$ are as follows:

c_1: Depreciation cost of equipment per unit of processed CR (sieving and screening machines) (AT1)

c_2: Energy cost of equipment per unit for CR processing (sieving and screening machines) (AT1)

c_3: Depreciation Cost of carbonization equipment usage per unit of carbonized material (AT2)

c_4: Energy cost of carbonization equipment usage (AT2)

c_5: Depreciation cost of CO_2 collect equipment usage per unit at the cement plant (AT3)

c_6: Energy cost of CO_2 collect equipment usage (AT3)

$$C = \begin{pmatrix} c_1 \\ \vdots \\ c_6 \end{pmatrix} \tag{2}$$

Thus, vector AC consists of items that represent the costs of activities (per unit) computed using Eq. 3 :

$$AC = B \cdot C = \tag{3}$$

$$\begin{pmatrix} b_{11} & \cdots & b_{16} \\ \vdots & \ddots & \vdots \\ b_{71} & \cdots & b_{76} \end{pmatrix} \cdot \begin{pmatrix} c_1 \\ \vdots \\ c_6 \end{pmatrix} = \begin{pmatrix} ac_1 \\ \vdots \\ ac_7 \end{pmatrix}$$

The next step involves allocating the respective quantities to the activities for the final product. Figure 1 also visualizes the quantity of materials at each activity. For instance, $'Q_{\mathrm{CR}}'$ represents the amount of CR arriving at the recycling facility, while Q_{RCA} and Q_{WCP} represents the amount of materials arriving at the concrete plant. Thus, those parameters can be represented as follows:

q_1 : Material quantity (CR) transported from a demolished site to a recycling plant (Q_{CR})

q_2 : Material quantity at RF (RCA and WCP, not carbonized: Q_{RCA}, Q_{WCP})

q_3: Material quantity at cement plant (CO_2 and cement: Q_{CO2}, Q_{Cem})

q_4: Natural materials quantity transported to a concrete plant (gravel and sand: Q_{NM}^{gravel}, Q_{NM}^{sand})

Therefore, the matrix 'Q' represents the allocation of material quantities to each activity (Eq. 4). In this matrix, the horizontal lines represent the quantity of materials ($q_1 \ldots q_4$) at different facilities, while the vertical lines correspond to the different activities ($a_1 \ldots a_7$). For example, $'q_{11}'$ stands for the quantity of CR transported from a demolishing site (DS) to a recycling plant, while $'q_{22}'$ and $'q_{32}'$ represents the quantity of RA and WCP at the recycling facility correspondently (not carbonized).

$$Q= \begin{matrix} DS \\ RF \\ CM \\ NM \end{matrix} \begin{pmatrix} q_{11} & q_{12} & \cdots & q_{17} \\ q_{21} & q_{22} & \cdots & q_{27} \\ q_{31} & q_{32} & \ddots & q_{37} \\ q_{41} & q_{42} & \cdots & q_{47} \end{pmatrix} \tag{4}$$

Final product cost (PC) can be determined by Eq. 5:

$$PC = Q \cdot AC = \begin{pmatrix} q_{11} & q_{12} & \cdots & q_{17} \\ q_{21} & q_{22} & \cdots & q_{27} \\ \vdots & \vdots & \ddots & \vdots \\ q_{41} & q_{42} & \cdots & q_{47} \end{pmatrix} \cdot \begin{pmatrix} ac_1 \\ ac_2 \\ \vdots \\ ac_7 \end{pmatrix} = \begin{pmatrix} pc_1 \\ pc_2 \\ \vdots \\ pc_4 \end{pmatrix} \quad (5)$$

For the environmental cost calculation, a matrix 'E' is utilized to represent the environmental cost per unit of the considered material. In this matrix, the horizontal rows correspond to various activities (a_1 to a_7) represented above, such as CR, RA, WCP, and CO_2 processing, while the vertical columns indicate CO_2 emissions per unit of material during specific processes (e_1). Environmental parameters are illustrated in Figure 1 as $E_1 - E_5$ and AE_1 - AE_4 and represented as column values below:

- e_1: Amount of CO_2 emissions by each equipment per unit of material *(a_i)* during recycling and carbonization processing (E1, E2)
- e_2: Amount of CO_2 absorption during the RCA and WCP carbonization (AE1)
- e_3: An environmental effect associated with soil and water contamination, as well as land occupation in landfills (AE2).
- e_4: Amount of CO_2 emissions by each equipment per unit of flue CO_2 collection (E3)
- e_5: Amount of captured CO_2 per unit of flue gases at the cement plant (AE3)
- e_6: Amount of CO_2 emissions per unit of cement produced (E5)
- e_7: Environmental effect related to the unit of natural material (gravel) processing for the concrete manufacturing (E4)
- e_8: Savings associated with the substitution of natural materials (gravel) per unit (AE4)
- e_9: An environmental effect related to the unit of natural material (sand) processing for concrete manufacturing (E4)
- e_{10}: Savings associated with the substitution of natural materials (sand) per unit (AE4)

The matrix 'E' is represented as Eq. 6. For instance, the matrix element $'e_{11}'$ indicates the amount of CO_2 emissions produced per unit of CR processed into RCA and WCP. In this context, CO_2 emissions are represented as negative values, while CO_2 sequestration is denoted as positive values.

$$E = \begin{matrix} CR \\ RCA \\ \vdots \\ NM_{sand} \end{matrix} \begin{pmatrix} e_{11} & e_{12} & \cdots & e_{1\,10} \\ e_{21} & e_{22} & \cdots & e_{2\,10} \\ \vdots & \vdots & \ddots & \vdots \\ e_{71} & e_{72} & \cdots & e_{7\,10} \end{pmatrix} \quad (6)$$

The environmental costs of activity drivers (per unit) can be represented as a column vector 'EC' (Eq. 7). The unit costs of activity drivers $e_1 - e_{10}$ are as follows:

- $ec_1, ec_2, ec_4 - ec_7, ec_9$: Environmental cost related to the unit of material recycling and carbonization
- ec_3: Environmental costs per unit of disposed material due to soil and water contamination and landfill occupation.
- ec_8: Cost per unit of substituted natural materials (gravel)
- ec_{10}: Cost per unit of substituted natural materials (sand)

$$EC = \begin{pmatrix} ec_1 \\ \vdots \\ ec_{10} \end{pmatrix} \quad (7)$$

Thus, vector 'EEC' consists of items that represent the environmental costs of activities (per unit) computed using Eq. 8:

$$\mathrm{EEC} = E \cdot \mathrm{E}C = \begin{pmatrix} e_{11} & \cdots & e_{1\,10} \\ \vdots & \ddots & \vdots \\ e_{71} & \cdots & e_{7\,10} \end{pmatrix} \cdot \begin{pmatrix} ec_1 \\ \vdots \\ ec_{10} \end{pmatrix} = \begin{pmatrix} eec_1 \\ \vdots \\ eec_7 \end{pmatrix} \quad (8)$$

Final product environmental cost (PEC) can be determined by Eq. 9:

$$PEC = Q \cdot \mathrm{EEC} = \begin{pmatrix} q_{11} & q_{12} & \cdots & q_{17} \\ q_{21} & q_{22} & \cdots & q_{27} \\ q_{31} & q_{32} & \ddots & q_{37} \\ q_{41} & q_{42} & \cdots & q_{47} \end{pmatrix} \cdot \begin{pmatrix} ec_1 \\ ec_2 \\ \vdots \\ ec_7 \end{pmatrix} = \begin{pmatrix} pec_1 \\ pec_2 \\ \vdots \\ pec_4 \end{pmatrix} \quad (9)$$

3 Case study

The Hong Kong concrete waste market was chosen as a case study due to the city's proactive approach in tackling local challenges. The government has implemented various initiatives aimed at enhancing CDW management and achieving carbon neutrality. Currently, the government's policy direction emphasizes further reduction of CDW and aligns with the global movement towards carbon neutrality. This strategy is reinforced by key government documents, including "Hong Kong's Climate Action Plan 2030+" [25], "Waste Blueprint for Hong Kong 2035" [26], and "The Chief Executive's 2022 Policy Address" [27]. The "Climate Action Plan 2030+" specifically outlines strengthened measures to combat climate change and establishes a target for reducing carbon emissions by 2030.

3.1 Data collection

To illustrate the practicality and feasibility of the proposed matrices, an assessment was conducted for the Hong Kong market, focusing on the Tseung Kwan O Area 137 Construction Waste Sorting Facility (TKO137SF) as a basis for integrating demolished concrete carbonization technology. Decisions and defined variables were quantified using reliable data obtained from a range of credible sources, including sustainability reports from government agencies, Hong Kong standards, a Life Cycle Assessment tool database, the Chinese life cycle database V0.8, and production specifications for recycled concrete. This information was incorporated into the ABC model matrixes to produce final results and facilitate a comparison of the two scenarios under consideration. The average quantity of incoming demolished concrete was determined based on statistics from the Environmental Protection Department and the Census and Statistics Department. The estimated annual amount of concrete rubble (CR) is 80,002 tonnes [28], assuming that 15% of this recycled material is transformed into WCP [29]. Consequently, the capacities of all considered equipment were calculated based on the average daily and yearly waste turnover. Separate calculations indicate that carbonizing this quantity of CR byproduct requires a total of 8,144 tonnes of CO_2 annually. Additionally, the amounts of substitute cement, gravel, and sand were determined based on standard concrete mix proportions.

3.2 Data processing and discussion

The obtained data is utilized to populate the matrices (B, C, Q, E, and EC), which are necessary for subsequent calculations, ultimately leading to the formation of the 'PC' and 'PEC' matrices. The final matrices associated with the environmental cost of the traditional method are represented in Eq. 10 (PEC_{trad}). In this context, the final product cost matrix (PC_{trad}) is not included, as it only accounts for additional equipment and resources while keeping the existing recycling processes unchanged. Negative numbers represent the loss of CO_2, while positive numbers indicate preserved CO_2. The vector element $'pc_1'$ reflects the recycling of CR through traditional methods, excluding any consideration of additional equipment, which is consequently equal to '0'. The vector element 'pc_2' is quantified at 2.4 million HKD per year, signifying the environmental impact related to soil and water contamination, as well as land occupation in landfills, due to WCP being directed to landfills instead of being recycled. Additionally, the vector element $'pc_3'$ represents the annual CO_2 emissions resulting from cement production that could potentially be mitigated through the use of WCP to capture CO_2 from the cement plant, amounting to 1.5 million HKD. Similarly, 'pc4' illustrates the annual CO_2 emissions associated with the expenditure on natural resources, totalling 125,505 HKD.

$$PEC_{trad} = \begin{pmatrix} 0.00 \\ -2,400,060 \\ -1,495,289 \\ -124,505 \end{pmatrix} \quad (10)$$

The final matrices for the product cost in the proposed recycling process are represented in Eq. 11, which details expenses related to additional technology integration and energy consumption. The vector element $'pc_1'$, approximately 3,964HKD, indicates the annual amortization cost and energy consumption needed to upgrade the existing equipment for recycling the annual quantity of CR and producing WCP in addition to RCA. This cost is relatively low, as only an additional mobile vibrating screen for sieving is required alongside the current capabilities. The elements $'pc_2'$ and $'pc_3'$ represent the additional equipment amortization costs and energy consumption for the carbonization of RCA and WCP, as well as the flue CO_2 collection, respectively. The energy consumption of the CO_2 collection equipment is quite high (19 kWh/tonne), resulting in an annual cost of nearly 1.5 million HKD.

In terms of environmental impact (Eq.12), CO_2 emissions occur during the processing of CR into RCA and WCP with $'pec_1'$ equaling -736HKD. In the subsequent carbonization stage (with $'pec_2'$ costing 6.3 million HKD per year), the CO_2 absorbed by RCA and WCP significantly outweighs the emissions from the energy used in the process. Additionally, saving landfill space plays a crucial role in enhancing environmental benefits. The vector element $'pec_3'$, approximately 5.1 million HKD per year, represents savings in cement manufacturing due to flue CO_2 collection and the substitution of cement with WCP, which has a considerable environmental impact. The highest figure, 28.3 million HKD per year (represented by 'pec_4'), reflects the conservation of natural materials (gravel and sand) in terms of preserving these resources and avoiding energy expenditure for their processing.

$$PC_{altern} = \begin{pmatrix} 3,964 \\ 139,540 \\ 1,479,910 \\ 0.00 \end{pmatrix} \quad (11)$$

$$PEC_{altern} = \begin{pmatrix} -763 \\ 6,294,267 \\ 5,090,160 \\ 28,275,866 \end{pmatrix} \quad (12)$$

Figure 2 illustrates that the annual costs for additional equipment investment and energy consumption in the proposed approach closely match the environmental costs of traditional methods. This alignment indicates that the alternative approach offers significant environmental benefits across all facilities involved. Moreover, by reducing carbon emissions, these facilities can engage in the carbon credit market, allowing them to buy and sell carbon credits. This provides a financial incentive for adopting greener technologies while contributing to sustainability goals. In summary, the proposed approach not only balances economic and environmental costs but also creates opportunities for revenue through carbon credits.

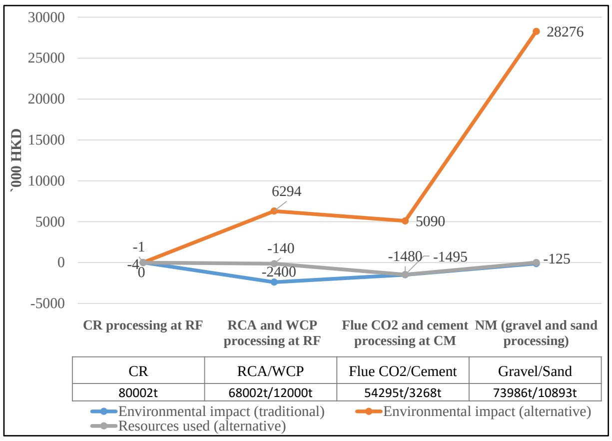

Figure 2. Cost comparison between traditional and proposed approaches.

4 Conclusions

This research explored the practicality and effectiveness of applying active carbonation techniques to WCP and RCA, using flue gases from cement manufacturing as a substitute source of CO_2 for the carbonization process. This innovative approach utilizes flue gases from cement plants for carbonation, significantly reducing the environmental costs associated with cement production and the processing and consumption of natural materials.

The comparison of environmental impacts between traditional and alternative demolished concrete recycling methods (PEC_{trad} and PEC_{altern}) reveals significant differences across all operations in the analyzed facilities. RCA and WCP processing at recycling facilities exhibits a 362% increase from traditional to alternative methods, transforming from -2,400 to 6,294kHKD. The collection of flue CO_2 and cement processing at the cement plant shows an even larger percentage change of 440%, rising from -1,495 to 5,090kHKD. The most significant difference is in natural material processing (gravel and sand), showing an increase of approximately 227kHKD in absolute terms, attributed to the conservation of natural materials and reduced energy expenditure for processing. These significant percentage increases and the shift from negative to positive values in most processes indicate a fundamental difference in environmental impact assessment between the two methodologies. Considering the environmental benefits of the proposed recycling approach that incorporates carbonization technology, the government should implement initiatives to promote this technology further, as it will enhance its ESG evaluation and align with overall policies aimed at reducing carbon emissions.

The universalization of the matrix can be expanded to adapt it to different configurations within the CDW supply chain. However, it's crucial to take into account specific conditions in the recycling market, such as issues related to illegal dumping, which may necessitate modifications to the model. The data were taken as the average quantity of demolished concrete, with other parameters adjusted to simulate and analyze the differences between approaches. The same matrices can be reused. Future research will explore broader implementation challenges, including logistical constraints and site-specific conditions, while examining how the Hong Kong-based model can be adapted to diverse global markets through considerations of varying regulatory frameworks, market maturity, consumer behavior patterns, and regional infrastructure development stages.

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