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Concrete Waste Management Decision Analysis Based On Life Cycle Assessment

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Malaysia, a developing country has always had a high level of construction activity. While it means economic growth, the waste generated by the construction industry has always posed a problem. Most of the construction waste is made up of concrete. The inert and non-hazardous concrete waste, suffers from weak enforcement provisions and this further escalates it into large scale landfill dumping and illegal dumping. The consequences of improper waste management are potentially alarming. With the rising concerns of waste management and global carbon concentrations, this study aims to evaluate the potential environmental impacts associated with concrete waste materials and to identify the best alternative in managing the concrete waste. A comprehensive life cycle assessment framework is proposed to assess the environmental impacts associated with the upstream and downstream of concrete waste life cycle; from raw material extraction to material processing, distribution to disposal or recycle. This study analysed the life cycle system in three scenarios: Scenario 1 depicts the cradle-to-grave scenario where concrete waste is sent to landfill without treatment and recycling. Scenario 2 and 3 depict the cradle-to-cradle scenarios in which the concrete waste is cyclically recycled into aggregates and reuse as road base material and reuse in recycled aggregate concrete production. With the compilation of a systematic life cycle inventory of relevant energy, fuel, and process emissions as inputs and released carbon emissions as outputs, this study helps in interpreting the environmental impacts of different waste management into a series of quantitative measures for more informed decision making. A construction project case study is modelled and analysed in the life cycle assessment framework to demonstrate the model's applicability. Results from this study suggest that the recycle of concrete waste into aggregates and reuse in recycled aggregate concrete production have the least GHG impact to the environment at 0.094 tCO_2. Recycling of concrete waste for road base material emits 0.095 tCO_2 and followed by landfilling at 0.139 tCO_2. This model intended to be an analysis and decision-making tool while embracing sustainable development stewardship.

1. Introduction

Construction and demolition waste continues to increase in parallel with the economic growth especially in the emerging and developing countries like Malaysia. Among all the type of waste, concrete waste (CW) occupied the highest percentage of total waste generated (Mah et al., 2016; Lachimpadi et al., 2012). In USA, approximately 200 Mt of concrete waste is generated every year (USEPA, 2016). Globally, CW generated is recycled and reused as road base material or to produce recycled aggregate concrete (RAC). In Australia, 90 % (CCANZ, 2011) of the CW produced is recycled and in Japan, recycling of CW has achieved 99.5 % recycling rate in 2012 (MLIT, 2014).

However, Malaysian CW management practices are principally guided by economic incentives such as low disposal cost, inexpensive and abundance of virgin material resources outweigh the recycling cost. The benefits derived from recycling CW could not offset the recycling cost, resulting in a large-scale of landfill dumping practices and low recycling rate. Even though CW itself is inert, non-hazardous, and does not produce GHG in landfill, yet the amount of CW occupying the amount of land in landfill somehow depletes the finite land resource. In Butera et al. (2015) study, it shows that the leachate caused by CW in landfill could

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potentially cause contamination to subsoil and groundwater too. In addition, with the country's pledge to achieve 40 % of reduction in the carbon emission intensity, current CW management practise need to move toward a green economy transition and lower carbon emissions practice.

Life cycle assessment (LCA) is a useful tool in conducting a systematic assessment focusing in the environmental impacts of the concrete life cycle from cradle to grave. LCA quantify all the inputs and outputs of the material flows and assessing how these inputs and outputs impact the environment. The impact assessment from LCA is useful as a decision-making tool to improve the current concrete waste management practise, particularly important in the green economy transition (Ondova and Stevulova, 2013). A number of international researchers have devoted applicable research in the development of construction and demolition waste, and concrete aggregate LCA. For instance, Mercante et al. (2012) conducted a LCA study to develop and analyse a life cycle inventory of construction and demolition waste (CDW) management system. Tao et al. (2016) study in a closed-loop concrete waste LCA based on cradle-to-cradle theory in China. However, even though many studies have reported the increased importance of LCA of concrete waste, there has been very little research reported in Malaysia.

The purpose of this study is to evaluate the potential environmental impacts associated with the CW management in an open-loop and closed-loop LCA and to identify the best alternative in managing the CW with a case study in Malaysia. The evaluation of the environmental impacts is done through life cycle assessment in examining the inputs and outputs of the material flows and accessing how the carbon emissions affect the environment.

The outline of this study is presented in a few sections. Section 1 is the introduction, research purpose and objective. Second section describes the research methodology, the scenarios development, assumptions, and analysis. Case study application, result analysis, and discussion are presented in section 3. The last section is the summary and conclusions of this study.

2. Methodology

Development of concrete LCA is according to LCA analysis defined in ISO 14040 and 14044. Figure 1 shows the study boundary in which it defines the concrete LCA in 3 types of scenarios. System boundary of this study defines the cradle-to-grave and cradle-to-gate scenarios. Three scenarios are built to allow the comparison of different waste management strategy. Scenario 1 is the business as usual scenario (BaU) where the CW generated from construction site (CS) is sent to landfill without treatment. Scenario 2 is where the CW is crushed in RP to produces CCA and to be reuse as road base material in road construction site (RCS). Scenario 3 is where the CW is crushed in RP and the CCA produces is uses as a substitution to VA in RAC production. Both scenarios 2 and 3 are set to be the countermeasure scenarios of BaU.

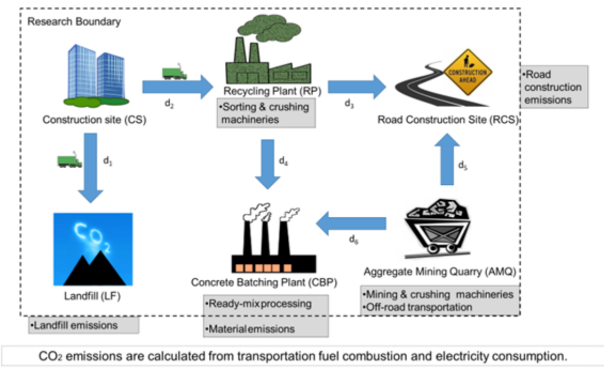

Figure 1: System boundary of CW life cycle assessment.

The type of emissions that are considered in this study included the energy and fuel emission from mining, extraction, and crushing of virgin aggregate (VA), energy emission from recycling plant (RP), fossil fuel combustion emission, and the avoided emissions from reusing crushed concrete aggregate (CCA).

The effective functional unit of this study is $kgCO_2/tCW$ disposed and $kgCO_2/tCW$ recycled. These assumptions and limitation were applied in this study:

- CW material is inert waste which is neither chemically or biologically reactive and will not decompose in landfill. In landfilling, CW does not emit CH_4 and N_2O, and both of the substances are not taken into account as part of the GHG emissions calculation.

- Carbon sink from landfilling is not considered in this study.
- The CO_2 emission from calcination process in cement manufacturing is not covered in this study.
- It is assumed that the substitution of CCA with VA in normal concrete and RAC productions does not affect the content of cement, sand, and water needed for the normal concrete and RAC productions. Thus, the emission from CCA substitution in RAC production is assumed to be neutral.
- The natural carbonation process occurs in building concrete and the uptake of CO_2 in re-carbonation of CCA are both not considered in this study.
- The carbon footprint of the construction of RP, concrete batching plant (CBP), and construction of machineries are excluded in this study.

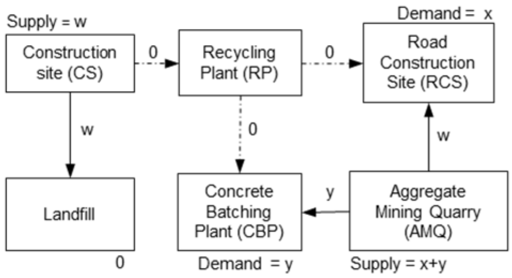

Figure 2: System boundary for scenario 1, BaU (landfilling)

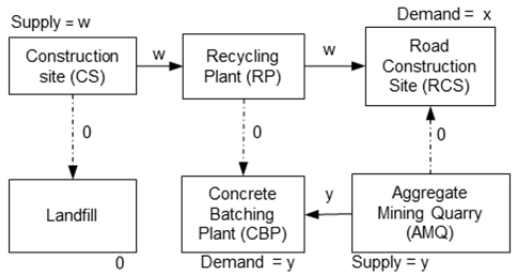

Figure 3: System boundary for scenario 2 where CW is recycled as road base material

Scenario 1 –BaU is the landfilling scenario. BaU is current waste management practise in the industry, where all the CW generated from the construction site (CS) is sent to the landfill without treatment. In general, landfilling is subjected to GHG emissions from transportation and machineries operation, landfill carbon storage, energy recovery, and CO_2 absorption in the CW in landfill. However, this study focused only on transportation emissions in anthropogenic CO_2 emissions from diesel combustion. Figure 2 shows the material flow of scenario 1. The amount of CW produces from the CS is assumed to be at w amount. In the RCS, the demand for aggregate material is assumed to be at x amount. In CBP, it needs y amount of aggregates to produces a ton of concrete. In this scenario, the w amount of CW is sent for landfilling, neither the RCS nor the CBP are benefited from the CW. Thus, the demand of aggregates for both the RCS and the CBP are fulfilled by VA, supplied by AMQ. The total supply of VA needed from AMQ is therefore assumed at $(x+y)$. Virgin aggregate is a product output from AMQ. To have a complete comparison between the scenarios, the emissions from AMQ for supplying VA to both RCS and CBP are also considered in this study. Figure 1 shows the complete system flows of CW and VA. Emissions from scenario 1 are calculated based on transportation fuel emissions and aggregate mining process emissions (Table 1). The CO_2 emission coefficients for transportation (E_t), recycling (E_r), and mining (E_m) are calculated from life cycle inventory data obtained from previous researches (Table 2). The value of E_t, E_r, and E_m are 0.14 $kg\text{-}CO_2\, t^{-1} km^{-1}$, 1.27 $kg\text{-}CO_2\, t^{-1} km^{-1}$ and 31.93 $\text{kg-}CO_2\, t^{-1}km^{-1}$. The d_1, d_5, and d_6 denote the distances between CS~LF, AMQ~RCS, AMQ~CBP.

Table 1: Total emissions from scenario 1 – BaU (landfilling)

Emissions	Transportation ($\text{kg-}CO_2\, t^{-1}$)	Mining or Recycle ($\text{kg-}CO_2\, t^{-1}$)
CW is sent to landfill	$E_t \times w \times d_1$	
AMQ supply VA to RCS	$E_t \times x \times d_5$	$E_m \times x$
AMQ supply VA to CBP	$E_t \times y \times d_6$	$E_m \times y$
Total emissions from Scenario 1	$E_t \times d_1 \times w + [E_t \times d_5 + E_m] \times x + [E_t \times d_6 + E_m] \times y$	

Scenario 2 – is the scenario where CW is sent to the RP for recycling, produces CCA and to be reuse as road base material in the RCS. CCA is the product output from RP and is produced through the processes of separation, crushing, and sieving of CW. CCA is used to replace VA up to a certain percentage in RAC production. In scenario 2, it is assumed that 100 % of the CW is recyclable and reusable as road base material. Thus, the w amount of CW is assumed to have fulfilled the x amount of demand from the RCS ($w=x$). Recycling of CW diverted the CW from being dump to landfill. The replacement of VA with CCA as road base material likewise reduced the mining emissions of the x amount of VA needed in RCS. In this scenario, the AMQ supply only y amount of VA to the CBP, while the demand for RCS is fulfilled by recycling of CW. Total emissions from scenario 2 are summarized in Table 3. The d_2, d_3, and d_6 denote distances of CS~RP, RP~RCS, AMQ~CBP.

Table 2: Calculation of emission factors

Transportation	Fuel Consumption (L/t-km)	Emission Factor ($kgCO_2/L$)		Emission $kgCO_2$/t-km	References
Truck Medium Heavy Class 6-7 (20 t)	0.052	2.66		0.14	(USEPA and NHTSA, 2016)
Mining Machineries	**Capacity (t/h)**	**Fuel Consumption (L/h)**	**Emission Factor ($kgCO_2$/km)**	**Emission ($kgCO_2$/t)**	
Extraction (CAT D9R dozzer) (16.4 m^3)	73.8	55	2.66	1.98	(Michalis, 2011)
Pusher / Excavator (CAT 330C excavator) (3 m^3)	73.8	30	2.66	1.08	
Loader (Volvo L180F 265kW) (4 m^3)	73.8	40	2.66	1.44	
Loader (Volvo L150F 265kW) (4 m^3)	73.8	38	2.66	1.37	
Primary crusher, secondary crusher, screen, hopper & feeder	200	346.5	0.51	0.89	
	Fuel Consumption (L/t-km)	**Emission Factor ($kgCO_2$/L)**		**Emission ($kgCO_2$/t-km)**	
Off-road mining truck (CAT 797F)	9.46	2.66		25.17	(CAT Caterpillar, 2013)
Emission from Aggregate Mining Quarry				31.93	
Recycling Plant Machinery		**Energy Consumption (kWh)**	**Emission Factor ($kgCO_2$/kWh)**	**Emission ($kgCO_2$/t)**	
Feed hopper		-			(Samyoung Plant Co., 2016)
Vibrating feeder (QH-1042) (200 t)		22	0.51	0.06	
Jaw crusher (FSK-4430) (200 t)		110	0.51	0.28	
First cone crushing (MC-200(A)) (200 t)		160	0.51	0.41	
Vibrating screen (OP3-2160) (200 t)		45	0.51	0.12	
Second cone crushing (MC-200(B)) (200 t)		160	0.51	0.41	
Emission from Recycling plant		497		1.27	

Table 3: Total emissions from scenario 2 where CW is recycled as road base material

Emissions	Transportation (kg-CO_2 t^{-1})	Mining or Recycle (kg-CO_2 t^{-1})
CW is sent to landfill	0	0
CW is sent to RP, produced CCA	$E_t \times w \times d_2$	$E_r \times w$
CCA is transport from RP to RCS	$E_t \times w \times d_3$	
AMQ supply VA to RCS	0	0
AMQ supply VA to CBP	$E_t \times y \times d_6$	$E_m \times y$
Total emissions from Scenario 2	$[E_t \times (d_2+d_3) + E_r] \times w + [E_t \times d_6 + E_m] \times y$	

Scenario 3 - is where CW is sent to RP for recycling, produces CCA and to be reuse as a replacement to VA in RAC production. In RAC production, there are many specifications limit on the percentage of replacement of VA by CCA. In Hong Kong and New Zealand, up to 100 % of CCA replacement is allowed and the RAC produces is acceptable for all non-structural applications. Meanwhile, in countries like UK, Australia, Korea, Germany, Portugal and Hong Kong, the allowable CCA substitution for structural concrete range from 20 % to 35 %, depending on the required RAC strength (CCANZ, 2011). However, the usage of CCA in RAC is likely to influence most of the concrete properties such as compressive strength, modulus of elasticity, shrinkage, and creep. The relative density of CCA is about 5 % - 10 % lower than the VA and this is because of the cement mortar that remains adhered to the aggregates. Nevertheless, RAC can be manufactured using 100 % CCA replacement where the processing of the CCA and the manufacture of the RAC are all closely controlled (CCANZ, 2011). In this study, we assumed that the allowable substitution of CCA is 50 % (VA:CCA = 1:1) to produce a unit of RAC. Thus, the CBP demand on aggregate to produce a unit of RAC is $y = 2w$. CW is sent to RP for recycling and only 50 % ($0.5w$) of CCA produced from RP is sent to CBP to produce RAC. The balance of the 50 % of CCA ($0.5w$) is assumed to be unsuitable material for RAC production and is reused in RCS as road base material. Hence, the supply of VA from the AMQ to the CBP is reduced by 0.5w and is defined as *y*-0.5*w* and the supply of VA from the AMQ to the RCS is defined as (*x*-0.5*w*). Recycling of CW to produces RAC and reuse in the RCS diverted the CW from being dump to landfill. Emissions from scenario 3 are calculated based on transportation fuel emissions, RP processing emissions, and aggregate mining process emissions (Table 4). The distances d_2, d_3, d_4, d_5, and d_6 are the distances between CS~RP, RP~RCS, RP~CBP, AMQ~RCS, AMQ~CBP.

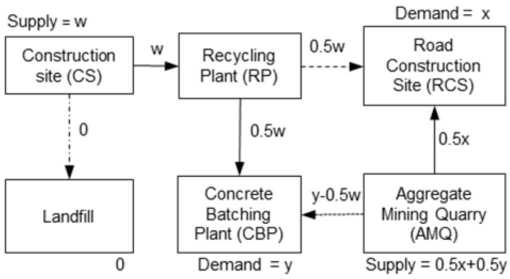

Figure 4: System boundary for scenario 3 where CW is recycled as road base material and reused to produces RAC.

Table 4: Total emissions from scenario 3 where CW is recycled as road base material and reused to produces RAC

Emissions	Transportation (kg-CO_2 t^{-1})	Mining or Recycle (kg-CO_2 t^{-1})
CW is sent to landfill	0	0
CW is sent to RP, produced CCA	$E_t \times w \times d_2$	$E_r \times w$
CCA is transport from RP to RCS	$E_t \times 0.5w \times d_3$	
CCA is transport from RP to CBP	$E_t \times 0.5w \times d_4$	
AMQ supply VA to RCS	$E_t \times (x-0.5w) \times d_5$	$E_m \times (x-0.5w)$
AMQ supply VA to CBP	$E_t \times (y-0.5w) \times d_6$	$E_m \times (y-0.5w)$
Total emissions from Scenario 3	$(E_t \times d_2+E_r)(w) + (E_t \times 0.5w)(d_3+d_4) + (E_t \times d_5+E_m)(x-0.5w) + [E_t \times d_6+E_m](y-0.5w)$	

3. Analysis and results

The scenario analysis is applied to a high-rise development construction project in Iskandar Malaysia, Johor Malaysia. Throughout the construction period of 3 y, the project generated approximately *w* = 3,049.63 t of CW and the distances between each destination are recorded in shortest driving distance. Transportation distances between each destination are obtained from plotting in the Google map. The distances are recorded based on the return trip of the shortest driving distance between the 2 destinations. The d_1 = 76 km, d_2 = 42 km, d_3 = 24 km, d_4 = 4 km, d_5 = 82 km, and d_6 = 76 km. In scenario 3, $y=2w$ = 6,099 t, $w=x$, 50 % of w is assumed to be the 50 % of x too. (0.5w = 0.5x=1,524.82 t). Results of the impact assessment are presented in Table 5.

Table 5: Total emissions from scenarios analysis

Total emissions	tCO_2	tCO_2 / tCW
Scenario 1 – BaU (landfilling)	422.9	0.139
Scenario 2 - CW is recycled as road base material	290.6	0.095
Scenario 3 - CW is recycled as road base material and reused to produces RAC	287.6	0.094

Results show that scenario 3 emits the least GHG at 287.6 tCO_2 / 3,049.63 tCW or 0.094 tCO_2 / tCW, followed by scenario 2 that emits 290.6 tCO_2. Scenario 1 emits the highest GHG at 370.8 tCO_2. Recycling of CW to produces RAC and to reuses as road base material (scenario 2 and 3) show significant reduction in total CO_2

emissions. Both scenarios emit 31 % - 32 % of CO_2 lesser as compared to scenario 1 of landfilling. Recycling of CW leads to reduction of CO_2 emissions since it avoids the emissions from virgin materials extraction and manufacturing.

The transportation emission from scenarios 2 and 3 are main contributor to total emissions and also a driving factor in determining the feasibility of both scenarios. For instance, the location of the landfill is located far away from the construction site (d_1 = 76 km), while the CBP is set up at just 4 km away from the RP (d_4 = 4 km) and in this case, recycling is seems more viable than landfilling. Sensitivity analysis in transport distances could help to refine the feasibility of the LCA results.

However, uncertainties do exist in this study as in both scenario 2 and 3, the process of removing mortar is not considered in the final emission factors and the CCA is reuse as-it-is condition. In reality, it is recommended to remove the mortar adhered to the CW before crushing it to becomes CCA. Mortar removal process will eventually add more to the GHG emissions.

4. Summary and Conclusions

The main findings of this study can be summarized as follows: while landfilling (scenario 1) of concrete waste emitted the highest carbon emissions, concrete waste is preferably to recycle as road base material and also to reuse as a substitution to virgin aggregate in recycled aggregate concrete production (scenario 2 and 3). Substitution of virgin aggregate with concrete waste shows significant benefits by reducing the necessity of landfilling, mining of virgin aggregate, and reduction in carbon emissions associated with energy and fuel consumption. Recycle and reuse of concrete waste could possibly reduce the overall environmental impact as compared to landfilling.

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