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Life Cycle Assessment of Precast Concrete Units

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***Abstract*—**Precast concrete has been widely adopted in public housing construction of Hong Kong since the mid-1980s. While pre-casting is considered an environmental friendly solution, there is lack of study to investigate the life cycle performance of precast concrete units. This study aims to bridge the knowledge gap by providing a comprehensive life cycle assessment (LCA) study for two precast elements namely façade and bathroom. The results show that raw material is the most significant contributor of environmental impact accounting for about 90% to the total impact. Furthermore, human health is more affected by the production of precast concrete than the ecosystems.

***Keywords*—**Environment, green, LCA, LCIA, precast.

I. INTRODUCTION

SUSTAINABLE development has attracted significant attention in recent years as the construction sector consumes a large amount of energy and produces lots of pollutants. This is particularly true for mega cities like Hong Kong not only because of the growing demand for construction facilities but also due to a desire for better quality of life as economic prospers. The average construction volume in Hong Kong amounts to around HK$100,000 million per annum [1] which is approximately 3% of the GDP [2]. The rapid development of construction facilities has given rise to a large amount of construction and demolition (C&D) waste with 37,690 ton of C&D waste being generated per day and deposited in landfills [3].

Precast (prefabricated) concrete units have been introduced to the public housing in Hong Kong by the Hong Kong Housing Authority (HKHA) since the mid-1980s as a measure to reduce the C&D wastes and improve the efficiency of construction. In 2002, precast units accounted for up to 17% of the concrete volume in public housing [4] in which half of Hong Kong people are inhabiting [5]. Compared with traditional cast in-situ concrete, pre-casting can reduce 65% of construction waste, 16% of labor on site, 15% of construction time [2], and 5% of carbon emission [6]. However, the use of precast concrete is hindered by its cost, inflexibility for change, longer time required for initial design, water tightness when applied to external locations, etc. [7]. Precast concrete has also been adopted in Europe, Singapore and Japan [7]. Although pre-casting is regarded as a more environmental friendly option, it is unclear if the environmental performance of precast concrete can outperform that of cast in-situ concrete.

Life cycle assessment (LCA) is a method to assess the environmental performance of a product over its entire or partial life cycle. The ISO 14040 [8] series defines four stages for a LCA study which include (i) goal and scope definition; (ii) life cycle inventory (LCI); (iii) life cycle impact assessment (LCIA); and (iv) interpretation. LCA has been adopted for green labeling, new product development, benchmarking, etc. Many LCI databases, like Ecoinvent and US LCI, are available which cover a wide range of materials, while SimaPro is a commercially available LCA tool which contains various LCI databases. However, a scrutiny of SimaPro's LCI databases reveals that there is a lack of data for precast concrete units. This creates an obstacle for implementing LCA studies in the construction sector.

This study aims to bridge the knowledge gap through comprehensive LCA case studies of two precast units namely façade and bathroom. The investigation covers the life cycle stages from 'cradle to gate' *viz.* raw material extraction, transportation, in-plant process, waste and recycle, and it embraces all the upstream processes before construction is started on site. With that, LCIA can be performed to unveil the environmental impacts, such as global warming, human toxicity, fossil depletion, eutrophication, etc., of the two precast concrete units in question.

II. MATERIAL AND METHODOLOGY

A. Scope of the Study

The in-plant procedures are much more complicated when it comes to manufacturing a precast unit than the traditional cast in-situ one. Nonetheless, the procedures to be carried out on construction site can be much more simplified when using the precast units as some works have already been transferred to the precast yard.

Materials like cement, sand, aggregate and admixtures are transported from the manufacturing factories to the precast yard. The mixing of these raw materials is conducted at the batching plant which is normally located within the precast yard. Reinforcements are cut and then installed according to the

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design. Concrete is then poured to the steel mold to form the precast elements and curing usually by means of water is needed to control concrete quality. Control cubes are made to check the strength, according to which the de-molding time can be calculated. The precast units are lifted to the storage area after de-molding. To ensure the quality is satisfactory, quality check is carried out at the storage location. Finally, the precast unit is transported to construction site. It is worth mentioning that the cut and waste of aluminum and reinforcement are usually returned to the manufacturing plant for recycling. The typical process flow of precast concrete units is shown in Fig. 1 where the upstream procedures from the ‘cradle to gate’ before construction are the focus of this paper.

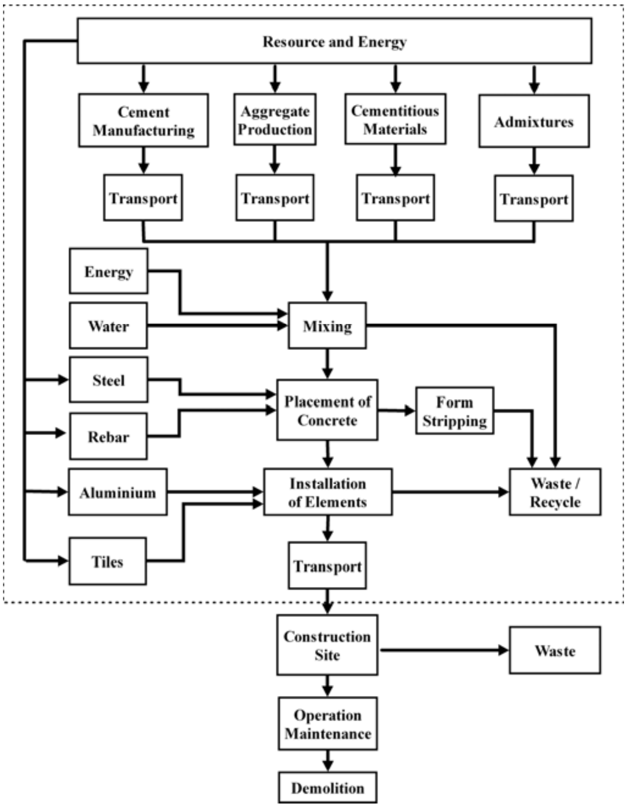


Fig. 1 General process map of life cycle of precast concrete

Precast façade is the mostly used precast element in Hong Kong [5] and volumetric precast bathroom is a relatively new precast product. This paper analyzes the two precast units being manufactured in mainland China (Fig. 2).

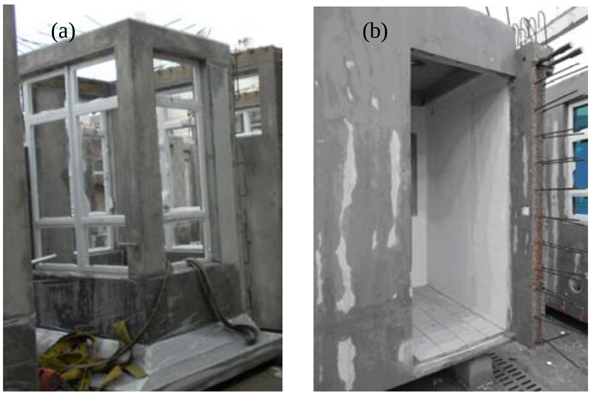


Fig. 2 (a) precast façade and (b) precast bathroom

B. Life Cycle Inventory

Field survey was conducted to observe the precast manufacturing processes and to collect the data for LCA model development. The input data is shown in Figs. 3-7 which include the proportions of raw material, transportation distance, in-plant energy, resource consumption, etc. The material proportion for precast façade is in general consistent with bathroom, while tiles are applied to the bathroom at the precast yard. The total weight of the precast unit is between 5,000 kg and 6,000 kg with 90% of its weight attributed to concrete.

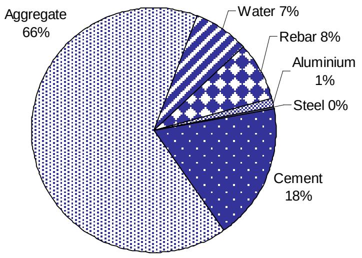


Fig. 3 Proportion of raw materials in a precast façade unit

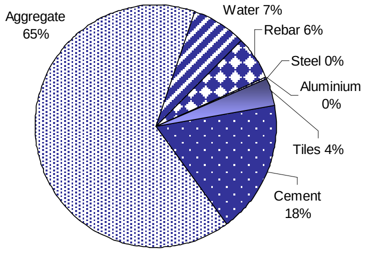


Fig. 4 Proportion of raw materials in a precast bathroom unit

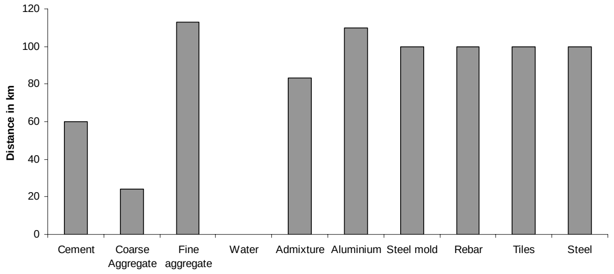


Fig. 5 Transportation distance of raw materials

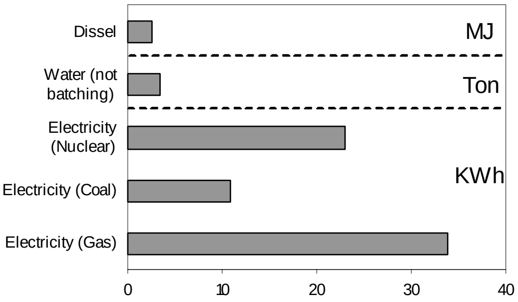


Fig. 6 Energy and water consumption in plant to produce a precast façade

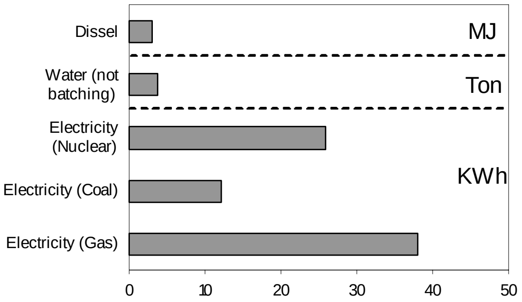


Fig. 7 Energy and water consumption in plant to produce a precast bathroom

Corresponding to the data collected, a LCA model is built to represent the five stages and according to the assumptions:

(i) Raw material

- Three types of concrete mix were produced during the report period and the average of the mix proportion is calculated according to their production;
- The density of admixture is assumed to be 1.2 kg/L;
- Tiles are taken as fully covering the floor and wall of a bathroom (width 1.5 m, length 1.5 m, height 2.7 m) with the areas of door and window being eliminated;
- The density of tile is assumed to be 15 kg/m^2 [9]; and
- One steel mold is used for 50 times. The amount of steel mold required for producing one precast unit is calculated by means of the weight of the precast unit and production in the report period.

(ii) Transportation of raw materials

- The transportation distance of raw materials is calculated by referring to the Google Maps;
- All the materials are transported by road; and
- The return distance is accounted for in LCI of ‘Truck 16t’, which assumes 40% efficiency.

(iii) Precast yard

- In-plant processes are calculated and they include mixing, molding, remolding, cutting reinforcement, manufacturing aluminum window frame, installing tiles and window frame, internal transportation, and storage;
- Electricity usage is allocated to façade and bathroom according to the weight and production of concrete in the report period;
- Allocation of electricity fuel type is based on the electricity power supply in mainland China; and
- The amount of non-batching water is by referring to the water bill and the amount of batching water in the concrete proportion.

(iv) Waste and recycle

- Water is recycled and reused within the plant and this can be accounted by the non-batching water;
- Materials such as aluminum, reinforcement and steel mold are returned to the factory for recycling;
- 1% of aluminum, reinforcement and steel will be recycled; and
- No other waste is generated for other materials.

(v) Transportation to site

- ‘Truck 28t’ is employed to simulate the stage of transportation to site;
- The distance is estimated by referring to the Google Maps.

C. Life Cycle Impact Assessment

In this study, a newly developed LCIA method known as ‘ReCiPe’ is adopted. ‘ReCiPe’ provides analysis at both the midpoint and endpoint levels [10]. For the midpoint version, it includes characterization and normalization, while the endpoint version includes additional damage assessment, weighting and single score. There are altogether 18 midpoint categories (or impact categories) and 3 endpoint categories (or damage categories).

The analysis is conducted using the midpoint and endpoint methods since the two methods lead to results with different perspectives. The midpoint method is based on environmental interventions by pollutant emission, resource consumption, etc. In contrast, the endpoint method focuses on the damage caused by those interventions.

SimaPro 7 is used to carry out LCI and LCIA. The ‘ReCiPe Midpoint (H) World H’ and ‘ReCiPe Endpoint (H) World H/A’ are adopted for the midpoint and endpoint analysis, respectively.

III. LCIA FOR RAW MATERIALS

In Table I, the LCIA is conducted for the primary materials, including cement, gravel, sand, reinforcement bar, aluminum, steel and tile, where the midpoint and endpoint results are shown. Five main midpoint categories are selected for the analysis according to their level of impacts (see Section IV). It is found that gravel and sand have least environmental impact while aluminum has the largest impact.

TABLE I
LCIA FOR THE PRIMARY RAW MATERIALS

	Mid [b]					End
Material [a]	CC	HT	IR	MD	FD	
	kg CO_2 eq	kg 1,4-DB eq	kg U235 eq	kg Fe eq	kg oil eq	
Cement	0.832	0.052	0.085	0.006	0.071	0.053
Gravel	0.004	0.002	0.007	0.001	0.001	0.001
Sand	0.002	0.000	0.002	0.001	0.001	0.000
Rebar	1.446	1.060	0.230	0.910	0.481	0.194
Aluminum	12.23	5.044	3.160	0.511	3.032	1.292
Steel	1.719	1.394	0.291	3.075	0.560	0.239
Tile	0.781	0.357	0.204	0.138	0.287	0.160

[a] The results are for per kg material
[b] CC climate change, HT human toxicity, IR ionizing radiation, MD metal depletion, FD fossil depletion

IV. RESULTS

A. Midpoint Results

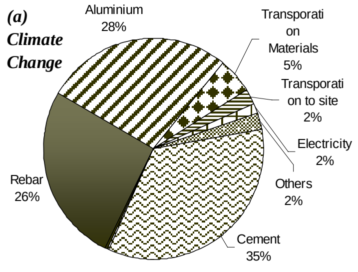
The midpoint results for precast façade and bathroom are given in Table II. The carbon emission to produce one façade is 2,346 kg per one precast element and the carbon emission of bathroom is 2,007 kg. The energy consumption for a precast façade is 535 kg oil eq while it takes 450 kg oil eq for bathroom. It is noted that the impacts on climate change, human toxicity, ionizing radiation, metal depletion and fossil depletion are significantly larger than the other categories.

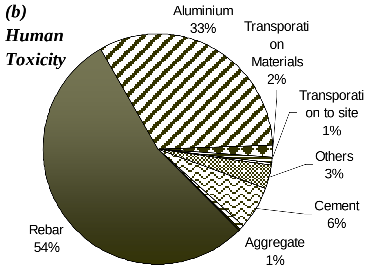
TABLE II
CHARACTERIZATION RESULTS OF PRECAST FAÇADE AND BATHROOM

Impact categories	Unit	Façade	Bathroom
Climate change	kg CO_2 eq	2346	2007
Ozone depletion	kg CFC-11 eq	0.0003	0.0003
Human toxicity	kg 1,4-DB eq	821.8	608.6
Photochemical oxidant formation	kg NMVOC	7.803	6.968
Particulate matter formation	kg PM10 eq	4.453	5.335
Ionizing radiation	kg U235 eq	424.4	332.9
Terrestrial acidification	kg SO_2 eq	7.491	5.842
Freshwater eutrophication	kg P eq	0.7130	0.4857
Marine eutrophication	kg N eq	0.3604	0.3011
Terrestrial ecotoxicity	kg 1,4-DB eq	0.1759	0.1297
Freshwater ecotoxicity	kg 1,4-DB eq	18.21	11.72
Marine ecotoxicity	kg 1,4-DB eq	18.86	12.19
Agricultural land occupation	m^2a	27.34	29.70
Urban land occupation	m^2a	11.64	13.00
Natural land transformation	m^2	0.30	0.26
Water depletion	m^3	23.85	23.04
Metal depletion	kg Fe eq	476.4	387.4
Fossil depletion	kg oil eq	535.3	450.5

Fig. 8 presents the contributions of various processes to the primary impact categories due to the production of one precast façade. In general, raw material is the primary contributor to these categories. For example, climate change accounts for 90% due to the use of cement, reinforcing bar and aluminum, while human toxicity is 54% and 33% as a result of the use of reinforcement bar and aluminum, respectively. Compared to raw material, transportation and in-plant processes contribute much less as they only account for less than 10% of the studied impact categories.

A contribution analysis for bathroom is given in Fig. 9, where the results are similar to those shown in Fig. 8 except for a more significant impact from tile and less from aluminum. This can be explained by examining Figs. 3-4, as a larger proportion of tile and smaller amount of aluminum can be detected for the precast bathroom. Raw material is still found to be the key contributor to those categories. Compared to façade, transportation accounts for a slightly larger impact, which is primarily due to the transportation of ceramic tiles.





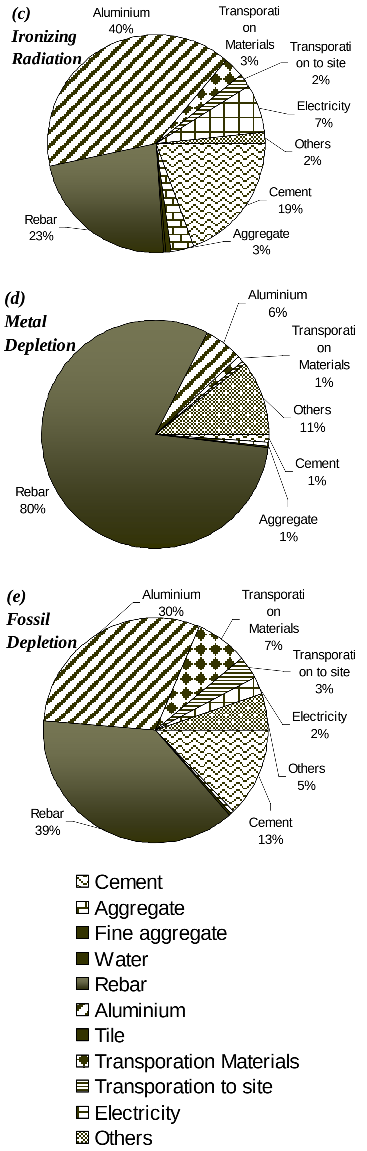
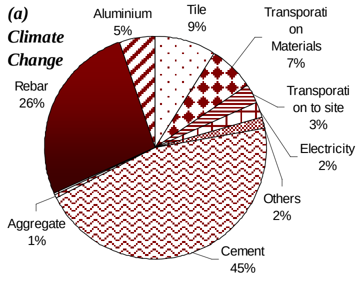


Fig. 8 Contribution analysis on the midpoint results of precast façade



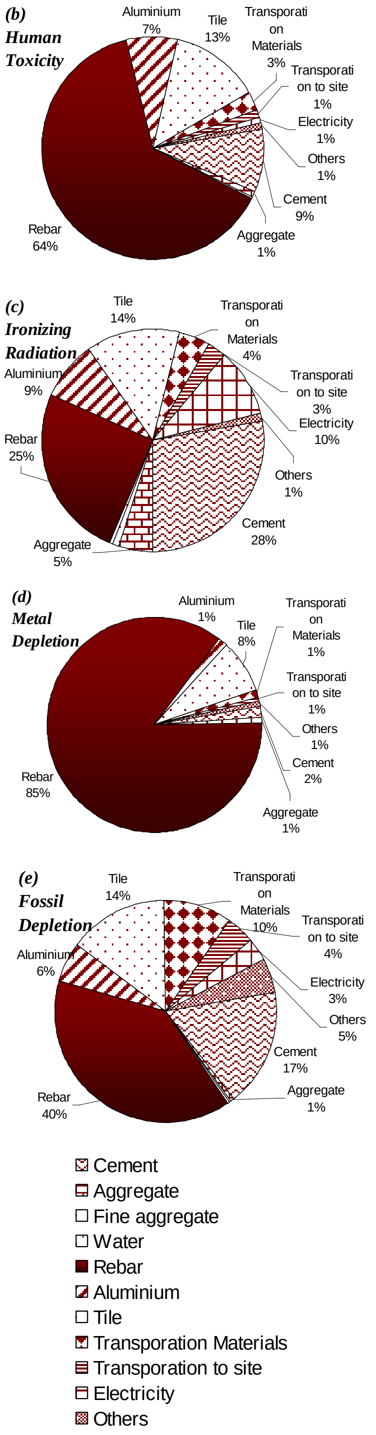


Fig. 9 Contribution analysis on the midpoint results of precast bathroom

B. Endpoint Results

The endpoint results of the three damage categories and the single total scores are shown in Table III. The value of the total score is the aggregation of all damage results. It is found that façade and bathroom have the total scores of 236 and 210, respectively.

Human health is the most contributive damage category to the final score, and the damage to human health is mainly due to climate change, human toxicity and ionizing as indicated in Table II. On the other hand, the damage to ecosystem resulted from eutrophication and ecotoxicity is less significant. The damage to resources is also obvious as a result of the use of fossil fuel and metal.

TABLE III
SINGLE SOCRE AND DAMAGE RESULTS OF PRECAST UNITS

Damage category	Façade	Bathroom
Single Score	*236*	*210*
Human Health	148	137
Ecosystems	9	7
Resources	78	65

V. DISCUSSION

The results generated by the LCA model indicate that the most significant impact of precast units is arising from raw materials rather than transportation and in-plant process. To improve the environmental performance therefore necessitates an efficient adoption of materials by recycling or reusing the waste materials such as steel, reinforcing bar and aluminum.

Sensitivity analysis has been carried out to calculate the total score of precast bathroom with the assumption that 90% of reinforcement bars are made of recycled material. With that, the total score can be effectively reduced by 63 points.

Another way to reduce the influence of raw material is to replace cement with cementitious materials, such as fly ash, blaster furnace slag, silica fume, etc. By substituting Portland cement by blaster furnace slag cement, the total score of precast bathroom can be decreased to 186.

On the other hand, transportation and in-plant processes, which have rather limited impact on the total performance, are resulting in a difference between traditional in-situ and precast concrete. The environmental benefit of precast concrete could be more obvious in the construction stage where wastage is reduced despite further investigations are needed to verify this observation.

VI. CONCLUSION

This study has investigated the environmental performance of two precast concrete units namely façade and bathroom by means of the LCA method. With the data collected through field survey, models have been established in SimaPro based on a new LCIA method – ‘ReCiPe’.

The results show that the production a façade and bathroom would result in a carbon emission of 2,346 kg CO_2 eq and 2,007 kg, respectively. The energy depletions are 535 kg oil eq and 450 kg oil eq due to the façade and bathroom, respectively. The total score of a precast façade unit is 236 whereas that for bathroom is 210.

Raw material is the primary contributor to the total impact while transportation and in-plant processes are less significant. Raw materials contribute to 90% of climate change and 94% of human toxicity. Human health is the most important damage category when compared with the ecosystems and resources. The damage to human health is due to climate change, human toxicity, ionizing, etc. On the other hand, the damage to the ecosystems is very small which contribute only 9 points in the case of façade and 7 points for bathroom.

The analysis in this study provides detailed LCA results of the two precast units, which can supplement current LCI databases. Investigation on the construction site is suggested as the advantage of precast concrete would be further identified in the on-site processes.

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