AUTOMATIC MEASUREMENTS OF CARBON EMISSIONS FROM BUILDING MATERIALS AND CONSTRUCTION FOR SUSTAINABLE STRUCTURAL DESIGN OF TALL COMMERCIAL BUILDINGS

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ABSTRACT: *Tall buildings are large-scale civil infrastructures that consume substantial amounts of construction materials and cause significant environmental impacts such as embodied carbon emissions. Understanding the effect of structural design (such as materials and structural forms) on the embodied carbon of building materials and the carbon emissions from construction activities is important to improve the sustainability of tall buildings. This study, with reference to the life cycle assessment (LCA) approach, aims to measure the carbon emissions from construction activities and from major building materials in tall buildings in order to underpin the sustainable structural design of tall commercial buildings. The formulations for carbon measurement are proposed, taking into consideration the cradle-to-site carbon emissions from material production, on-site construction, and waste disposal and treatment, with application of locally or regionally specific emission factors. Next, an automatic measurement tool based on the proposed formulations is developed to evaluate the carbon emissions of a tall commercial building, One Taikoo Place, in Hong Kong. The choice of structural materials has critical effects on the structural behavior of the tall building, which in turn substantially impacts the amounts of material consumption and carbon emissions. This study provides deeper understandings and interesting insights into the carbon performance of tall buildings for different structural designs relevant to the Hong Kong built environment. The results also provide a basis for constructing more environmentally friendly and cost-efficient tall buildings, contributing to a sustainable built environment for mankind.*

KEYWORDS: embodied carbon, climate change, cradle-to-site, life cycle assessment, structural design, sustainable construction, tall buildings

1. INTRODUCTION

The construction industry is a vital sector in the world's economy, contributing to the economic growth and long-term development of many countries. Embodied carbon from buildings materials and carbon emissions from construction activities are seen as an increasingly important area in making buildings more environmentally sustainable and resource efficient (Gan et al, 2020). The carbon emissions from material production and construction activities account for 27% of a building's life cycle carbon emissions (Halcrow Yolles, 2010). Hence, reducing embodied carbon is important not only for reducing resources and associated costs but also mitigating longer-term risks from resource availability. Junnila and Horvath (2003) was an early attempt to measure the embodied carbon from building material production for a five-story office tower. Blengini (2009) evaluated the potential of carbon reduction due to the reuse and recycling of demolition wastes. Previous studies have been focused on the carbon emissions from the construction of low-rise residential houses or buildings with 20 to 30 stories in heights (Scheuer et al., 2003; Gustavsson et al., 2010). There are needs for case studies to demonstrate the relationship between the carbon emissions and structural design of tall buildings. In addition, the information regarding the embodied carbon of construction materials was available in the life cycle inventories including the Inventory of Carbon & Energy (Hammond et al., 2011). The international carbon auditing guidelines for the life cycle of a product or a process (such as ISO 14067:2018, PAS 2050:2011 and the Greenhouse Gas Protocol) were also available. However, the values of embodied carbon in the inventories and/or carbon auditing methods are region-specific because the fuel mix and raw material resources vary in different countries or regions. The previous studies in other regions may not be applied directly to Hong Kong's context, therefore a locally specific study is needed to quantify and mitigate the embodied carbon of building materials and carbon emissions from construction.

Therefore, this paper presents the measurement of the embodied carbon from major buildings materials and carbon emissions from construction activities to underpin the sustainable structural design of tall buildings in the Hong Kong context. The formulations for cradle-to-site carbon measurement are presented, taking into account of the emissions from resource extraction, material manufacturing, transportation, on-site construction, waste disposal, sewage discharge and treatment. We made references to local publications and guidelines on carbon auditing, including the Guidelines to Account for and Report on Greenhouse Gas Emissions and Removals for Buildings in

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Hong Kong developed by Environmental Protection Department and Electrical and Mechanical Services Department (HKEPD and HKEMSD, 2010). Next, an automatic measurement tool based on the proposed formulations is developed to evaluate the carbon emissions of a 48-story tall building, One Taikoo Place, in Hong Kong. The carbon emission hotspots in the One Taikoo Place development project are identified, and the recommendations on carbon reduction are given based on the results of the study for future development projects.

2. METHODOLOGY

2.1 Presenting Case Study

The building chosen for the study is One Taikoo Place located at 979 King's Road, Hong Kong. Completed in 2018, One Taikoo Place is the first of two new triple Grade-A office towers in Swire Properties' HK$15 billion Taikoo Place redevelopment project. One Taikoo Place was designed with the highest green building and wellness standards in mind. It is the first commercial building in Asia to achieve WELL Core & Shell Final Platinum, and it is also the first commercial building in Hong Kong to obtain a triple Platinum rating (WELL, BEAM Plus and LEED Final Platinum certification).

The gross floor area of One Taikoo Place is 1 million square feet. This 48-storey office tower was constructed mainly from reinforced concrete using a core-frame structure. Structural steel outriggers are also constructed near mid-level to connect the exterior frame with the central core to improve the lateral stability of the building. Table 1 summarizes the amounts of building materials and energy sources for the construction of One Taikoo Place.

Table 1: Consumption of materials for One Taikoo Place

Materials or Energy	Consumption	Unit
Concrete (Grade 20/20D 75mm)	277,920	kg
Concrete (Grade 30/20D 125mm)	906,960	kg
Concrete (Grade 35/20D 125mm)	2,905,920	kg
Concrete (Grade 45/10D 125mm)	693,600	kg
Concrete (Grade 45/20D 125mm)	28,800	kg
Concrete (Grade 45/20D 125mm WP with Caltite)	78,928,080	kg
Concrete (Grade 45/20D 200mm)	34,119,600	kg
Concrete (Grade 60/20D 200mm)	25,787,760	kg
Concrete (Grade 60/20D 200mm WP with Caltite)	30,837,120	kg
Concrete (Grade 80/20D 200mm)	7,893,840	kg
Reinforcement bar	27,398,220	kg
Structural steel	1,224,717	kg
Timber formwork	1,355	m^3
Glass - Curtain wall, from Spain	97,483	kg
Glass - Curtain wall, from Shanghai	97,483	kg
Glass wall	103,080	kg
Electricity	467,560	kWh
Diesel	17,359	litre

The assessment of carbon emissions for this study is based on a cradle-to-site life cycle, which requires the assessment of emissions from producing the materials used in construction, the emissions arising from material transportation, as well as various on-site construction, waste disposal and treatment activities. The carbon emissions are expressed in terms of a functional unit, i.e. kilogram of carbon dioxide equivalent per construction floor area of the building (i.e. kg CO_2-e/m^2). The carbon emissions include three major types of greenhouse gases, namely carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O)[1]. Different carbon emissions are then converted into CO_2 equivalent using their respective global warming potentials. The proposed formulations cover both direct and indirect sources of carbon emissions. Equations for calculating each source of carbon emissions are illustrated in the following subsections.

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[1] The other types of greenhouse gases, hydrofluorocarbons (HFCs), nitrogen triflouride (NF_3), sulphur hexafluoride (SF_6), and perfluorocarbons (PFCs), are not included in the measurement because their contributions to the cradle-to-site carbon emissions of this building are negligible.

2.2 Formulations for Carbon Measurement

2.2.1 Total Carbon Emissions of the Project

The total carbon emissions due to embodied carbon of building materials and carbon emissions from construction activities can be calculated as follows:

$$E_T = [E_1 + E_2 + E_3 + E_4] \cdot A^{-1} \tag{1}$$

wherein E_T stands for the total carbon emissions per construction floor area of a tall building (kg CO_2-e/m^2) throughout the cradle-to-site life cycle, E_1 represents the material embodied carbon, E_2 refers to the carbon emissions due to various construction activities, E_3 refers to the carbon emissions due to waste disposal, E_4 is the carbon emissions due to the processing of fresh water and sewage, A represents the construction floor area of the building (m^2).

2.2.2 Embodied Carbon of Building Materials

Embodied carbon of building materials includes the emissions due to energy consumption for resource extraction and material manufacture as well as the carbon emissions from transportation for building materials. Below is the formula for calculating the embodied carbon of building materials with references to Gan et al. (2017a):

$$E_1 = \sum_{i=1}^{I} V_i CE_i + \sum_{i=1}^{I}\sum_{j=1}^{J} Q_i D_{i,j} CE_j \tag{2}$$

where V_i represents the quantity of building material i (m^3), CE_i stands for the carbon emission factor (kg CO_2-e/m^3). Q_i refers to the weight of building material i (kg), $D_{i,j}$ is the distance of transportation for material I (km), CE_j refers to the carbon emission factor for transport means j (kg CO_2-e/tonne·km). Table 2 summarizes the material embodied carbon emission factors used in the case study (One Taikoo Place). The emission factors for different transportation means are taken from WRI and WBCSB (2011), including truck and trailer at 0.204 kg CO_2-e/tonne·km, railway at 0.017 kg CO_2-e/tonne·km, and marine shipment at 0.048 kgCO_2-e/tonne·km.

2.2.3 Carbon Emissions from On-site Fuel and Electricity Consumption

The carbon emissions from fuel combustion and electricity consumption for on-site construction equipment can be calculated as:

$$E_2 = \sum_{e=1}^{E}\sum_{c=1}^{C} E_{ec}\, CE_e \tag{3}$$

in which E_{ec} is the consumption of fuel or electricity e by construction equipment c, CE_e is the carbon emission factor of fuel or electricity e. Table 3 shows the carbon emission factors for different fuel and electricity sources with references to local standards or publications.

2.2.4 Carbon Emissions due to Waste Disposal, Fresh Water Consumption and Sewage Treatment

The emissions from waste disposal did not include emissions generated from waste decomposition at landfill. Since local contractors utilize mainly diesel-based heavy-duty vehicles to dispose the construction wastes, the carbon emissions can be calculated as:

$$E_3 = \sum_{l=1}^{L} R_l \cdot CE_d \tag{4}$$

wherein R_l refers to the product of transportation distance for waste l (km) and the energy consumption indicator of vehicle for waste disposal (litre/km), CE_d is the carbon emission factor of diesel obtained from HKEPD and HKEMSD (2010), which is usually 2.64 kg CO_2-e/litre. The carbon emissions due to electricity used for fresh water consumption and sewage treatment are calculated with reference to HKEPD and HKEMSD, 2010:

$$E_4 = W \times (f_1 + \varepsilon f_2) \tag{5}$$

where W is the amount of fresh water consumed on the construction site (m^3), f_1 and f_2 are the electricity

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emission factors for the processing of fresh water and sewage (kg CO$_2$-e/m^3), and ε is the percentage of fresh water that enters the sewage system. In this study, all wastewater is assumed to be treated onsite and discharged to storm drain, and thus no discharge into the sewage system.

Table 2: Embodied carbon emission factor for different building materials used in One Taikoo Place

Materials	Emission factor	Unit	Description
Rebar (BF-BOF) – 100% Recycled[a]	0.84	kgCO$_2$-e/kg	Localized to Hong Kong context according to the literature
Rebar (BF-BOF) – 13% Recycled[b]	2.07	kgCO$_2$-e/kg	
Structural steel (BF-BOF) – 10% Recycled[c]	2.16	kgCO$_2$-e/kg	
Concrete (G20/20D)	262	kgCO$_2$-e/m^3	First-hand data (HKUST)
Concrete (G30/20D 125mm)	222	kgCO$_2$-e/m^3	Carbon emission factors provided by the main contractor
Concrete (G35/20D 125mm)	230	kgCO$_2$-e/m^3	
Concrete (G45/10D 125mm)	280	kgCO$_2$-e/m^3	
Concrete (G45/20D 125mm WP with Caltite)	272	kgCO$_2$-e/m^3	
Concrete (G45/20D 125mm)	257	kgCO$_2$-e/m^3	
Concrete (G45/20D 200mm)	295	kgCO$_2$-e/m^3	
Concrete (G60/20D 200mm)	295	kgCO$_2$-e/m^3	
Concrete (G60/20D 200mm WP with Caltite)	326	kgCO$_2$-e/m^3	
Concrete (G80/20D 200mm)	271	kgCO$_2$-e/m^3	
Glass	1.20	kgCO$_2$-e/kg	First-hand data (HKUST)
Timber-Plywood for Formwork	1.97	kgCO$_2$-e/kg	ICE Database (Hammond et al., 2011)

a. Carbon emissions of steel vary greatly due to the manufacturing processes such as Blast Furnace and Basic Oxygen Furnace (BF-BOF) or Electric Arc Furnace (EAF) as well as the content of recycled steel scrap. Below is a list of the carbon emission factors of rebar and structural steel collected from Gan et al. (2017a):

- Pig iron (BF-BOF) – 100% Virgin (2.09 kgCO$_2$-e/kg), Direct-reduced iron (EAF) – 100% Virgin (1.54 kgCO$_2$-e/kg), Direct-reduced iron (EAF) – 100% Recycled (0.39 kgCO$_2$-e/kg)
- Finished steel material – Rebar (0.16 kgCO$_2$-e/kg), Finished steel material – Structural steel (0.21 kgCO$_2$-e/kg)

The emission factors for the EAF process rebar are calculated based on the percentage of recycled scrap used. For example, the emission factor for the EAF process rebar with 21% recycled content can be calculated as: 1.54 x (1-21%) + 0.39 x 21% +0.16 = 1.459 kg CO$_2$-e/kg.

According to World Steel Association (WSA, 2011), the emission factor for BF-BOF rebar (13% scrap) is equal to: 2.09–13% × 1.41 + 0.16 = 2.07 kg CO$_2$-e/kg; the emission factor for BF-BOF structural steel (10% scrap) is equal to: 2.09–10% × 1.41 + 0.21 = 2.16 kg CO$_2$-e/kg.

b. The study applied U.S. Green Building Council's definition of the overall recycled content: The overall recycled content = (1/2 pre-consumer recycled content + post-consumer recycled content), which means the same amount of pre-consumer recycled content provide haft environmental benefit compared with post-consumer recycled content.

c. The emission factor for structural steel (BF-BOF) follows a similar calculation procedure as Notes a and b.

Table 3: Emission factor for different energy sources

Energy source	Emission factor	Unit	References
Electricity-CLP	0.54	kgCO$_2$-e/kwh	CLP,2017
Electricity-HKE	0.79	kgCO$_2$-e/kwh	HKE,2017
Towngas	2.82	kg/unit	HKEPD & HKEMSD, 2010
Diesel	2.617	kgCO$_2$-e/l	HKEPD & HKEMSD, 2010
LPG	1.679	kgCO$_2$-e/l	HKEPD & HKEMSD, 2010
Kerosene	2.432	kgCO$_2$-e/l	HKEPD & HKEMSD, 2010
Petrol Oil	2.707	kgCO$_2$-e/l	HKEPD & HKEMSD, 2010
Biodiesel (B5)	2.6	kgCO$_2$-e/l	Acquaye et al., 2012

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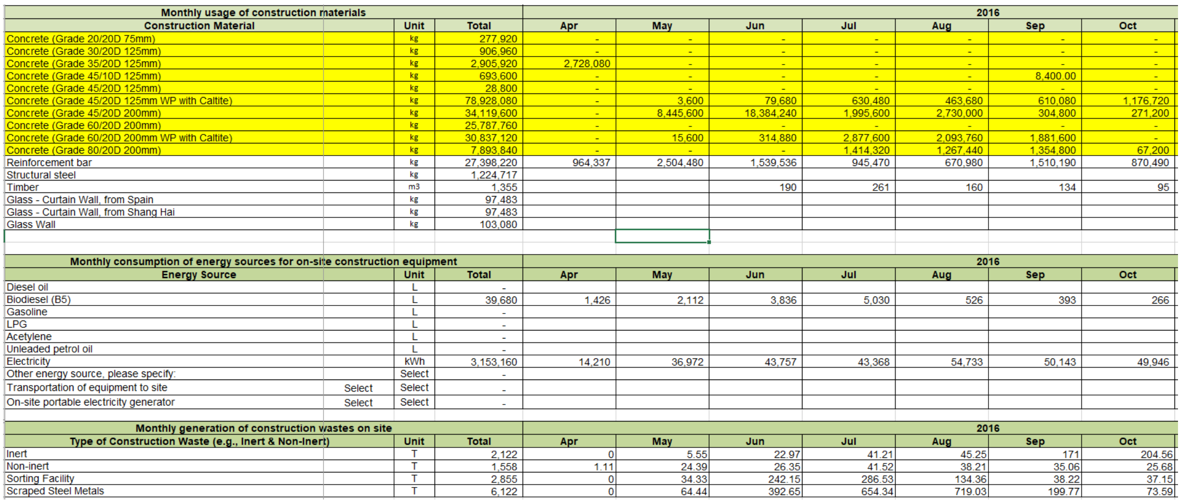
2.3 Automated Measurement Tools

2.3.1 Data Collection Template

Based on the formulations, site-specific data are collected for individual processes and materials used for One Taikoo Place (see Figure 1). The calculation considers the embodied carbon of major building materials (including concrete, rebar, structural steel, glass and timber formwork) as well as various construction activities. Hence, the data collection template is designed to cover all the major building materials and construction activities afore mentioned. Because difficulties may arise where data is not easily available, some assumptions are made for inputs where the collection of site-specific data is not practicable to allow the calculation. For example, the extraction and manufacture location of timber formwork is assumed within Hong Kong with a transportation distance to project site of 20 km. In addition, the density for timber formwork is 570 kg/m^3 with a maximum three times of reuse on average.



Monthly usage of construction materials				2016						
Construction Material		Unit	Total	Apr	May	Jun	Jul	Aug	Sep	Oct
Concrete (Grade 20/20D 75mm)		kg	277,920	-	-	-	-	-	-	-
Concrete (Grade 30/20D 125mm)		kg	906,960	-	-	-	-	-	-	-
Concrete (Grade 35/20D 125mm)		kg	2,905,920	2,728,080	-	-	-	-	-	-
Concrete (Grade 45/10D 125mm)		kg	693,600	-	-	-	-	-	8,400.00	-
Concrete (Grade 45/20D 125mm)		kg	28,800	-	-	-	-	-	-	-
Concrete (Grade 45/20D 125mm WP with Caltite)		kg	78,928,080	-	3,600	79,680	630,480	463,680	610,080	1,176,720
Concrete (Grade 45/20D 200mm)		kg	34,119,600	-	8,445,600	18,384,240	1,995,600	2,730,000	304,800	271,200
Concrete (Grade 60/20D 200mm)		kg	25,787,760	-	-	-	-	-	-	-
Concrete (Grade 60/20D 200mm WP with Caltite)		kg	30,837,120	-	15,600	314,880	2,877,600	2,093,760	1,881,600	-
Concrete (Grade 80/20D 200mm)		kg	7,893,840	-	-	-	1,414,320	1,267,440	1,354,800	67,200
Reinforcement bar		kg	27,398,220	964,337	2,504,480	1,539,536	945,470	670,980	1,510,190	870,490
Structural steel		kg	1,224,717							
Timber		m3	1,355			190	261	160	134	95
Glass - Curtain Wall, from Spain		kg	97,483							
Glass - Curtain Wall, from Shang Hai		kg	97,483							
Glass Wall		kg	103,080							

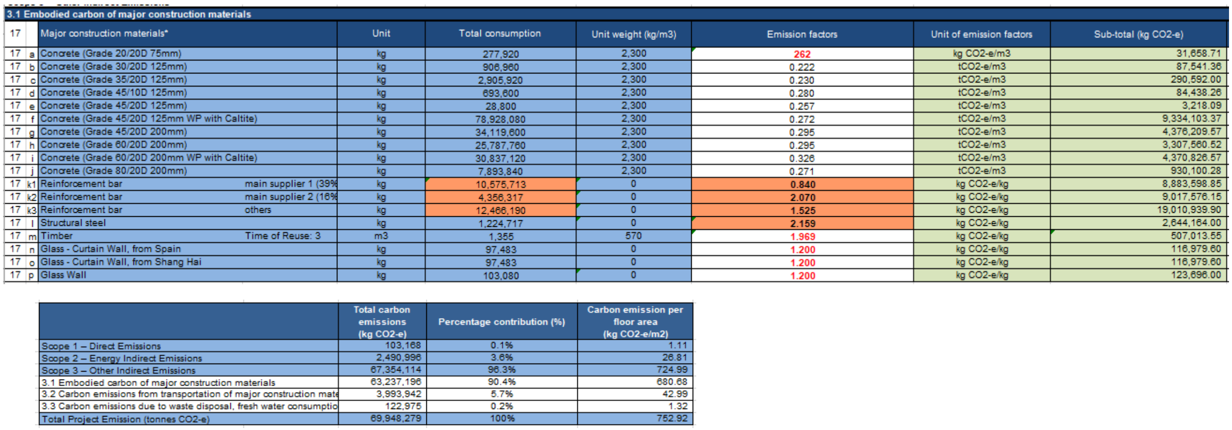
Monthly consumption of energy sources for on-site construction equipment				2016						
Energy Source		Unit	Total	Apr	May	Jun	Jul	Aug	Sep	Oct
Diesel oil		L	-							
Biodiesel (B5)		L	39,680	1,426	2,112	3,836	5,030	526	393	266
Gasoline		L	-							
LPG		L	-							
Acetylene		L	-							
Unleaded petrol oil		L	-							
Electricity		kWh	3,153,160	14,210	36,972	43,757	43,368	54,733	50,143	49,946
Other energy source, please specify:		Select	-							
Transportation of equipment to site	Select	Select	-							
On-site portable electricity generator	Select	Select	-							

Monthly generation of construction wastes on site				2016						
Type of Construction Waste (e.g., Inert & Non-Inert)		Unit	Total	Apr	May	Jun	Jul	Aug	Sep	Oct
Inert		T	2,122	0	5.55	22.97	41.21	45.25	171	204.56
Non-inert		T	1,558	1.11	24.39	26.35	41.52	38.21	35.06	25.68
Sorting Facility		T	2,855	0	34.33	242.15	286.53	134.36	38.22	37.15
Scraped Steel Metals		T	6,122	0	64.44	392.65	654.34	719.03	199.77	73.59

Fig. 1: Data collection template for inputting the consumption of building materials and energy sources.

2.3.2 Automatic Measurement

Based on the site-specific data collected, carbon emissions are evaluated automatically. Figure 2 shows the automatic measurement tool for calculating the carbon emissions from various building materials and construction activities. The automatic measurement tool, based on a spreadsheet format, reads the consumptions of building materials and energy sources in the data collection template. Next, it estimates automatically the amount of carbon emissions in accordance with the material quantities and corresponding carbon emission factors. The calculated carbon emissions are summarized in terms of three scopes, which are (1) direct greenhouse gases emissions, (2) energy indirect greenhouse gases emissions, and (3) other indirect greenhouse gases emissions. The results show the carbon emission sources towards identifying relevant mitigation measures to control and reduce the carbon emissions.



3.1 Embodied carbon of major construction materials									
17		Major construction materials*		Unit	Total consumption	Unit weight (kg/m3)	Emission factors	Unit of emission factors	Sub-total (kg CO2-e)
17	a	Concrete (Grade 20/20D 75mm)		kg	277,920	2,300	262	kg CO2-e/m3	31,658.71
17	b	Concrete (Grade 30/20D 125mm)		kg	906,960	2,300	0.222	tCO2-e/m3	87,541.36
17	c	Concrete (Grade 35/20D 125mm)		kg	2,905,920	2,300	0.230	tCO2-e/m3	290,592.00
17	d	Concrete (Grade 45/10D 125mm)		kg	693,600	2,300	0.280	tCO2-e/m3	84,438.26
17	e	Concrete (Grade 45/20D 125mm)		kg	28,800	2,300	0.257	tCO2-e/m3	3,218.09
17	f	Concrete (Grade 45/20D 125mm WP with Caltite)		kg	78,928,080	2,300	0.272	tCO2-e/m3	9,334,103.37
17	g	Concrete (Grade 45/20D 200mm)		kg	34,119,600	2,300	0.295	tCO2-e/m3	4,376,209.57
17	h	Concrete (Grade 60/20D 200mm)		kg	25,787,760	2,300	0.295	tCO2-e/m3	3,307,560.52
17	i	Concrete (Grade 60/20D 200mm WP with Caltite)		kg	30,837,120	2,300	0.326	tCO2-e/m3	4,370,826.57
17	j	Concrete (Grade 80/20D 200mm)		kg	7,893,840	2,300	0.271	tCO2-e/m3	930,100.28
17	k1	Reinforcement bar	main supplier 1 (39%	kg	10,575,713	0	0.840	kg CO2-e/kg	8,883,598.85
17	k2	Reinforcement bar	main supplier 2 (16%	kg	4,356,317	0	2.070	kg CO2-e/kg	9,017,576.15
17	k3	Reinforcement bar	others	kg	12,466,190	0	1.525	kg CO2-e/kg	19,010,939.90
17	l	Structural steel		kg	1,224,717	0	2.159	kg CO2-e/kg	2,644,164.00
17	m	Timber	Time of Reuse: 3	m3	1,355	570	1.969	kg CO2-e/kg	507,013.55
17	n	Glass - Curtain Wall, from Spain		kg	97,483	0	1.200	kg CO2-e/kg	116,979.60
17	o	Glass - Curtain Wall, from Shang Hai		kg	97,483	0	1.200	kg CO2-e/kg	116,979.60
17	p	Glass Wall		kg	103,080	0	1.200	kg CO2-e/kg	123,696.00

	Total carbon emissions (kg CO2-e)	Percentage contribution (%)	Carbon emission per floor area (kg CO2-e/m2)
Scope 1 – Direct Emissions	103,168	0.1%	1.11
Scope 2 – Energy Indirect Emissions	2,490,996	3.6%	26.81
Scope 3 – Other Indirect Emissions	67,354,114	96.3%	724.99
3.1 Embodied carbon of major construction materials	63,237,196	90.4%	680.68
3.2 Carbon emissions from transportation of major construction mate	3,993,942	5.7%	42.99
3.3 Carbon emissions due to waste disposal, fresh water consumptio	122,975	0.2%	1.32
Total Project Emission (tonnes CO2-e)	69,948,279	100%	752.92

Fig. 2: Automatic measurement tool in spreadsheet format for calculating carbon emissions of One Taikoo Place

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3. RESULTS AND DISCUSSION

3.1 Carbon Emissions per Construction Floor Area

The proposed formulations and automated measurement tools are examined in evaluating the carbon emissions of One Taikoo Place in Hong Kong. Table 4 shows the carbon measurement results for each emission scope. The results indicated that Other Indirect Emissions significantly outweighs the Direct Emissions (from energy combustion on-site) and Indirect Emissions (from electricity consumption). Of the Other Indirect Emissions, embodied carbon of major building materials accounts for the majority (90.4%) of the total emissions. The percentage contribution of each building material is calculated and summarized in Figure 3.

Table 4: Cradle-to-site carbon measurement results

Scope of carbon measurement	**Carbon emissions (kg CO_2-e)**	**Percentage contribution (%)**	**Carbon emission per floor area (kg CO_2-e/m^2)**
Scope (1) – Direct emissions	103,168	0.1%	0.8
Scope (2) – Energy indirect emissions	2,490,996	3.6%	20.5
Scope (3) – Other indirect emissions	67,354,114	96.3%	553.8
3.1 Embodied carbon of major building materials	63,237,196	90.4%	519.9
Concrete	22,816,249	32.6%	187.6
Rebar	36,912,115	52.8%	303.5
Structural steel	2,644,164	3.8%	21.7
Glass and timber	864,669	1.2%	7.1
3.2 Carbon emissions from transportation of major building materials	3,993,942	5.7%	32.8
Concrete	537,197	0.8%	4.4
Rebar	3,116,832	4.5%	25.6
Structural steel	166,836	0.2%	1.4
Glass and timber	173,077	0.2%	1.4
3.3 Carbon emissions due to waste disposal, sewage water treatment	122,975	0.2%	1.0
Total carbon emissions	69,948,279	100.0%	575.1

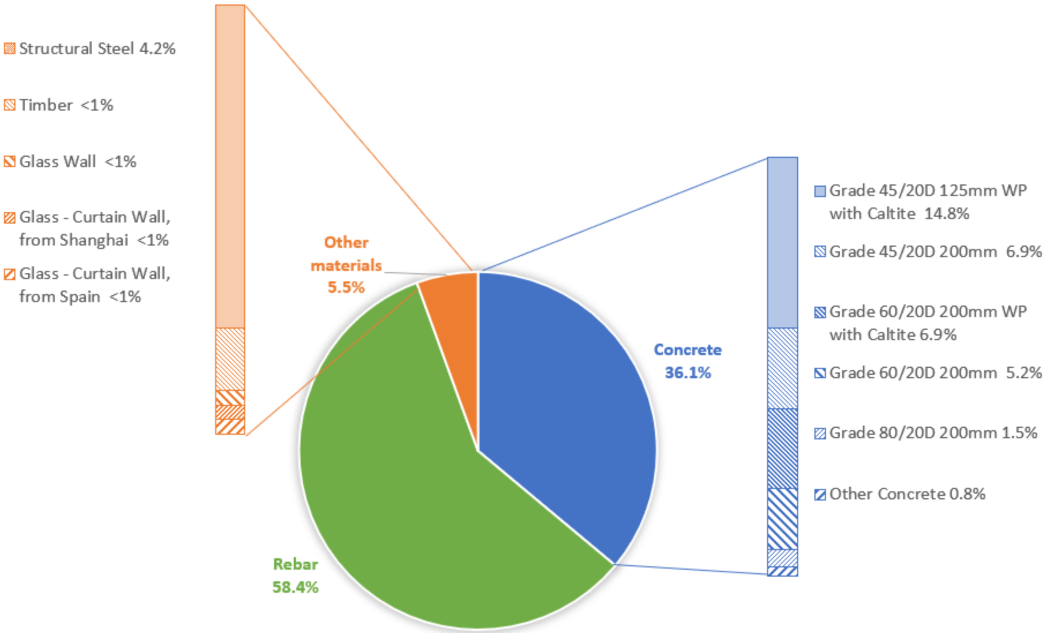

Fig. 3: Breakdown of cradle-to-gate embodied carbon for individual building material

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It is demonstrated that rebar and concrete contribute over 94% of the total cradle-to-gate embodied carbon of building materials. Specifically, rebar accounts for about 58% of the total cradle-to-gate embodied carbon, whereas concrete contributes 36% in which Grade 45, Grade 60, and Grade 80 concrete represent approximately 35%. On the other hand, the quantity of glass used in the project is much smaller than concrete, and therefore glass contributes less than 1% of total embodied carbon even though it has a much higher emission factor than concrete. Moreover, the carbon emissions due to the transportation of glass is also negligible (i.e. 0.17% of project's total carbon emissions) although the glass curtain wall are manufactured in Spain and Shanghai, which are far away from the construction site. As such, the carbon reduction strategy should emphasize the embodied carbon of construction materials, particularly from rebar and concrete.

3.2 Recommendations for Sustainable Structural Design

3.2.1 Design of Structural Systems

One Taikoo Place is a 48-storey building constructed mainly from reinforced concrete, using a core-frame structure. Structural steel outriggers are also utilized near mid-level to connect the external frame with the central core. Despite there is no benchmark of embodied carbon for such a 48-storey building using core-frame structure with steel outriggers from the literature, previous relevant study (Gan et al., 2017b) has indicated that the cradle-to-site embodied carbon per gross floor area for a 40-storey core-frame structure using the composite construction method (i.e. mixed use of structural steel and reinforced concrete) is 557 kg CO$_2$-e/m^2. If the 40-storey core-frame structure changes to the application of 100% structural steel, embodied carbon per floor area increases by around 36% to 759 kg CO$_2$-e/m^2. On the other hand, using 100% reinforced concrete reduces the embodied carbon of a core-frame structure by 4% to 537 CO$_2$-e/m^2. There are outriggers utilized in One Taikoo Place to enhance the lateral stability. The carbon emissions of these highly carbon intensive structural steel contribute 3.8% out of total embodied carbon and consequently increase the embodied carbon for One Taikoo Place. Another reason is that One Taikoo Place is a 48-storey building, which is 8-storey taller than the building considered in the literature, and therefore it may be exposed to a stronger wind profile. As a result, larger member size and more structural materials may be needed to reduce the lateral drift caused by wind force. It is recommended to study the embodied carbon for building using core-frame structure with steel outriggers to make a comparison with other typical structural forms (core-frame structure, core-outrigger, and mega-brace structures) for high-rise buildings and provide a benchmark for further comparison in future.

3.2.2 Design of Structural Materials

The embodied carbon of concrete, rebar and structural steel contributes to over 89% of total carbon emissions in One Taikoo Place. Utilizing recycled materials can greatly affect the total embodied carbon of One Taikoo Place. The section below presents the maximum possible carbon reduction by utilizing recycled concrete or steel.

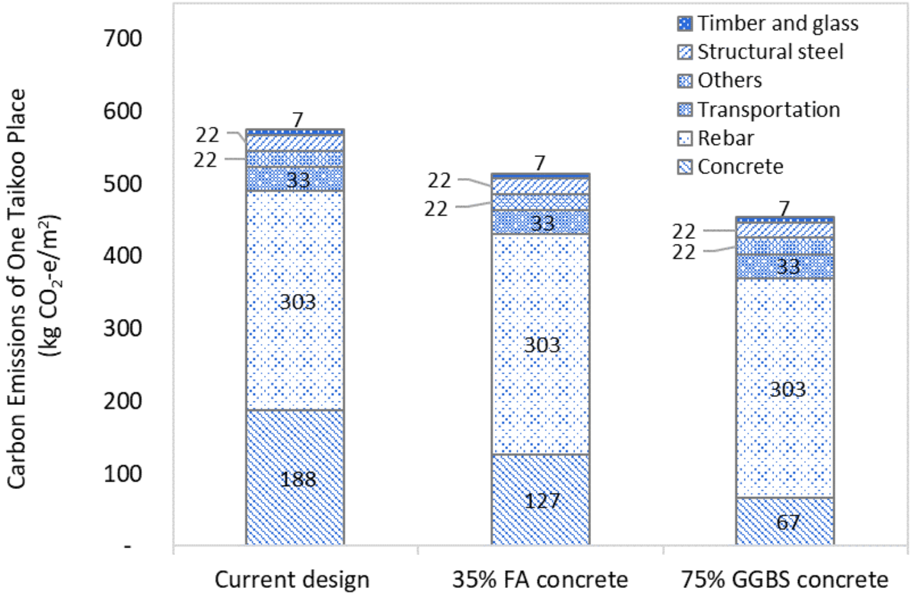

Fig. 4: Carbon emissions of One Taikoo Place with different types of concrete materials: 35% FA concrete and 75% GGBS concrete.

Gan, V.J.L., Li, X., Lo, I.M.C., Tse, K.T., Cheng, J.C.P., Chan, C.M., Ho, P., Lai, A., Law, J., Kwok, R., and Yau, R. (2020) "Automatic measurements of carbon emissions from building materials and construction for sustainable structural design of tall commercial buildings." *Proceedings of the 8th International Conference on Innovative Production and Construction (IPC 2020)*, Hong Kong, China, 7-8 December 2020.

The carbon emissions of concrete are affected by the addition of cement substitutes, e.g. fly ash (FA) and ground granulated blast slag (GGBS). According to the Hong Kong Code of Practice (HKBD, 2013), the maximum rates for cement substitution are 35% FA and 75% GGBS, respectively. Figure 4 shows that utilizing 35% FA concrete can help reduce the embodied carbon of One Taikoo Place from 574 to 514 kg CO_2-e/m^2 (equivalent to 11% reduction), while the use of 75% GGBS concrete can minimize the carbon emissions to 454 kg CO_2-e/m^2 (i.e. 21% reduction). However, when the GGBS in the concrete increased from 0% to 70%, the setting time will be extended from 100 mins to 200 mins (Suresh and Nagaraju, 2015). Hence, the contractor shall consider if the construction schedule is allowable for longer setting time when use high portion of cement substitutes (e.g. 75% GGBS). In addition, FA is a by-product of coal combustion (Li, 2011), which can be obtained from local coal-based power plants. GGBS, however, is a BOF or EF by-product from the iron & steel manufacturing industry (Li, 2011). Since there are no steel factories in Hong Kong, material availability and procurement status should be taken into account when formulating the carbon reduction measures.

In this study, around 88% of the steel rebar are manufactured via BF-BOF production method. The first largest supplier provided 39% of the rebar, which is BF-BOF steel with 100% recycled scrap. The second largest supplier provided 16% of the rebar used in the building, which is BF-BOF steel containing 13% recycled scrap. The rest of rebar suppliers (around 45%) provided either BF-BOF or EAF steel with recycled scrap ranging from 5.5% to 100%.

To facilitate the calculation and analysis, BF-BOF steel containing recycled scrap less than 30% is increased to the maximum allowable content of 30% (WSA, 2014). The emission factors of steel rebar decrease by 4% to 9%. Figure 5 reveals that the use of BF-BOF steel with 30% scrap can help reduce embodied carbon in the One Taikoo Place by 4% from 575 to 549 kg CO_2-e/m^2. In addition to BF-BOF, EAF is an alternative steel production technology, which can make use of up to 100% recycled scarp. If One Taikoo Place project can use 100% recycled EAF steel, the emission factor of steel rebar can be decreased by 64%, and the most significant reduction in building embodied carbon can be achieved (380 kg CO_2-e/m^2), which is 34% less than that of the current design.

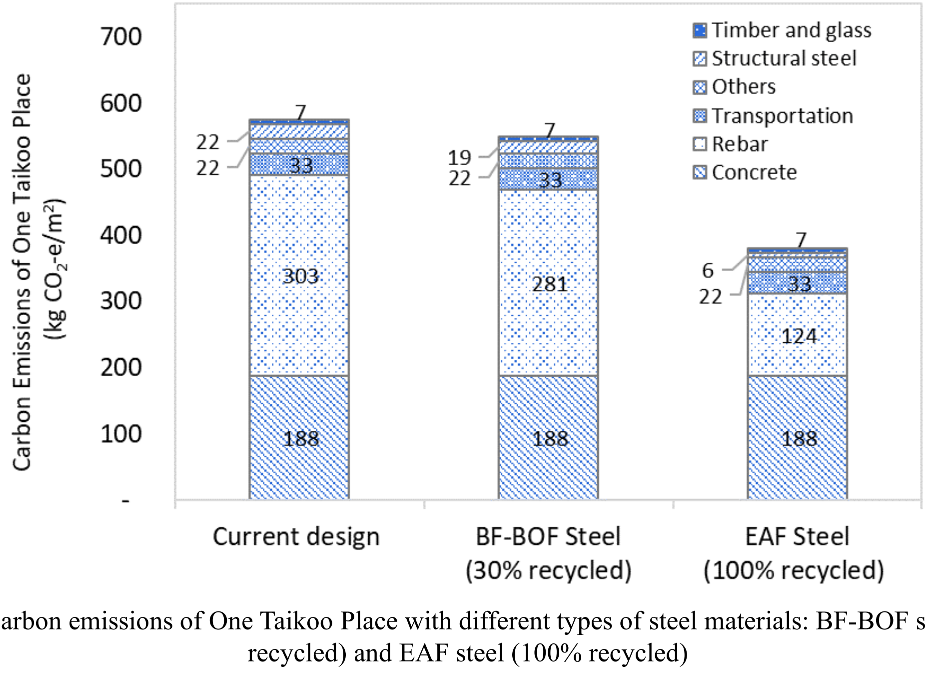

Fig. 5: Carbon emissions of One Taikoo Place with different types of steel materials: BF-BOF steel (30% recycled) and EAF steel (100% recycled)

3.2.3 Improvement Opportunities for Future Projects

At the beginning of the study, first-hand data are expected to be collected from material manufacturers for the calculation of carbon emission factors of the major building materials. The emission factors for concrete are obtained from the main contractor, who operates its own concrete batching plants and have obtained carbon labels for its concrete products. However, first-hand data are still needed from the suppliers of other materials such as rebar, structural steel, timber formwork, and glass. The data to be collected should cover the raw materials, energy consumption for material manufacture, amount of recycled content, fuel mix, and type of the production technologies, which in reality are very difficult to obtain due to the confidentiality issue, lack of operational control, etc. As such, it is recommended to plan the data collection and to specify the data request (e.g. in the contract) so that material manufacturers or suppliers can provide corresponding data for carbon auditing exercises.

In addition, the embodied carbon of a building is sensitive to certain building design parameters (such as material specifications and structural form design). More attentions should be paid to the collection of design parameters that significantly impact the building embodied carbon. For instance, the carbon emission factor of concrete varies considerably with increasing concrete strength. These material specifications, including the strength, production technology, and recycled content, should be clearly described during the data collection. In addition to material specifications, different types of structural forms also affect the structural efficiency and the amount of materials required. It is suggested to collect details of significant design parameters to facilitate the analysis of the carbon emission hotspots and to provide more insights on the embodied carbon reduction measures. It also helps decision makers to develop corresponding low carbon strategy for climate mitigation.

Last but the least, the embodied carbon associated with the production of rebar, structural steel and concrete contributes to 89.2% of total carbon emissions in One Taikoo Place. This is followed by the carbon emission from transportation of rebar, structural steel and concrete to the project site (5.5%) and carbon emissions from on-site electricity consumption (3.6%). The embodied carbon and carbon emissions from transportation of timber and glass account for only 0.73% and 0.75% of the total embodied carbon, respectively. Based on the rule of thumb in the specification for the assessment of life cycle greenhouse gas emissions of goods and services, a threshold of 1% is commonly used to exclude those minor carbon emission sources over the product life cycle. However, it should also be noted that the total exclusions should not exceed 5% of the overall product carbon emissions. It is suggested that when carrying out similar carbon accounting exercises, the scope can be properly defined to exclude the subtle carbon emission sources (such as timber formwork and glass) in order to save the workload and effort for data collection. Moreover, the carbon emissions due to the production and transportation of glass account for less than 1% of project's total carbon emissions. Therefore, glass can be also excluded from the scope of study. More attentions can be put on the data collection, evaluation, and analysis of the major carbon emission sources such as the embodied carbon of concrete and steel rebar.

4. CONCLUSIONS

This paper presents the measurement of carbon emissions from construction activities and building materials to underpin the sustainable structural design of tall commercial buildings. Formulations for carbon measurement are proposed, taking into consideration of the cradle-to-site emissions associated with resource extraction, material manufacturing, transportation, on-site construction and waste disposal and treatment, with application of locally or regionally specific emission factors. An automatic carbon measurement tool is developed to quantify the amount of carbon emissions from One Taikoo Place, Hong Kong. The results provide deeper understandings into the environmental performance of tall commercial buildings for different structural designs. However, several limitations still exist which call for improvements for future development projects. First, it is recommended to plan the data collection and to specify the data request so that material manufacturers or suppliers can provide associated data at the beginning of the study for carbon auditing. In addition, it is suggested to collect details of significant design parameters at the beginning of the carbon measurement so as to facilitate the analysis and to provide more insights on the embodied carbon reduction measures. Last but not least, more attentions should be spent on the data collection, evaluation, and analysis of the major carbon emission sources such as the embodied carbon of concrete and steel rebar.

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