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EMBODIED CARBON EMISSIONS OF CONSTRUCTION MATERIALS: A CASE STUDY OF BUILDINGS IN THAILAND

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ABSTRACT: With respect to moving towards development without threat to our future generations, the overwhelming unsustainable consumption of natural resources is the dominant energy and environmental concerns discussed in both international and national conferences. In particular, to find potential solutions to minimize environmental impacts, the building sector should priorly be considered since it is responsible for almost forty percent of both global energy and materials consumption and contributes around one-third of the global greenhouse gases emission. This research, therefore, aimed at evaluating the level of embodied carbon emissions derived from building construction materials, using four buildings located in an educational institute as a case study to represent the environmental performance of construction materials based on reinforce concrete structure in a tropical climate. The results revealed that on weighted average, the mass intensity and embodied carbon intensity of construction materials were 1,627 kg/m^2 and 322 kgCO$_2$/m^2. In addition, the taller the building height the more likely it was to help improve such intensities. Almost 90% and 69% of the mass intensity and embodied carbon intensity derived from structural component materials whereas 24% of the embodied carbon emissions attributed to decorating component materials. The results also indicated that improvement in building with reinforce concrete structure could focus only on six materials namely concrete, steel, aluminium, cement, paint, and ceramic tile since these materials contributed 94% of embodied carbon emission. The findings will be useful for planning proactive strategies in mitigating embodied carbon in building to cope with the challenges of global warming in the future.

Keywords: Embodied carbon emission, Educational building, Building materials, Construction phase, Reinforce concrete structure

1. INTRODUCTION

Globally, the building sector has played an important role in moving towards sustainable development goals as it accounts for 40% of the energy consumption, 40% of the raw materials use, 12% of the potable water consumption, one-third of the carbon emission and 40% of the waste to landfill [1,2]. Numerous studies of buildings to date mostly focused on reducing the energy consumption in the operation phase in order to decrease the amount of carbon emission [3,4]. However, the construction phase performance should be taken into consideration since the amount of material used for building construction will proportionally affect the level of the total building's embodied carbon, while different types of building material will additionally result in different amounts of energy demand in the operation phase [5,6].

In Thailand, although a quarter of theconstruction permission for commercial buildings was found to be for schools and institutions, less than 1% of such number are regulated under the energy conservation act [7,8]. An enormous amount of resources is prioritized for the educational system with the aim to enhance capacity building and support the needs of the country, but the efficiency of resource consumption has not been considered to any depth.

This study, therefore, aimed at evaluating the level of embodied carbon emissions derived from building construction materials of four buildings located in an educational institute in Thailand and identifying the key materials effecting the proportion of embodied carbon intensity in order to propose alternative solutions for minimizing the environmental impacts throughout the building service life. The findings will be useful for building owner or decision maker in designing a sustainable building based on a low carbon approach and in planning proactive strategies in mitigating embodied carbon of building to help cope with the challenges of global warming in the future.

2. METHODOLOGY

2.1 Description of the Building Cases

Four buildings with different purposes at Chulalongkorn University, located in Bangkok Thailand were assessed to evaluate the environmental performances through analysis of mass intensity (MI) and embodied carbon emission (ECI). The four building cases were built based on the reinforce concrete structure. Three of them were classified as a mix-used building with a total floor area of 16,143 m^2, 21,627 m^2 and 3,225 m^2 for Building A (12-storey building served with conference rooms, classrooms, laboratory rooms, research units, and a gym), Building B (13-storey building occupied with classrooms, conference rooms, offices and a cafeteria) and Building C (2-storey building with a cafeteria on the ground floor and an information center on the first floor) respectively, whilst the last (Building D) was a 17-storey dormitory building with total floor area of 31,500 m^2. Due to the difference in building sizes, in order to be comparable, a square meter of floor area was used as a functional unit to quantify each building's performances.

2.2 Building Materials Analysis

Regarding the building components, the construction materials in this study were classified into four categories named structural materials (SM), decoration materials (DM), materials supplied for ventilation and air condition (VA) system, and for sanitary and fire protection (SF) work. To analyze the building construction performance, either data of material types or quantity were obtained from the bill of quantities. In particular, 20 different types of building material that are commonly used in building construction were addressed, then a record of each material number was calculated in term of kg/m2 as demonstrated in equation 1.

$$MI = \sum_{j=1}^{4} \sum_{i} (Q_i \div A) \quad (1)$$

Where MI – mass intensity (kg/m^2) represents the consumption rate of construction materials, Q – quantity (kg) represents an amount of material used, A – area (m^2) represents a total floor area of building, i refers to the type of materials, and j refers to the four class of construction component (SM, DM, VA, SF).

2.3 Carbon Emission Assessment

Embodied carbon emission of a building is the emission that arises from the consumption of all materials used in the construction process. The boundary of such emission calculation involves raw material extraction, transportation from the raw material site to the material production plant, and the production process of material. Due to a lack of available data in Thailand, the BEES (Building for Environmental and Economic Sustainability) database was used as an emission factor (EF) to determine the embodied carbon emissions as demonstrated in equation 2.

$$ECI = \sum_{j=1}^{4} \sum_{i} (MI_i \times EF_i) \quad (2)$$

Where ECI - embodied carbon intensity ($kgCO_2/m^2$) represents the carbon emissions rate of the construction materials and EF – emission factor ($kgCO_2/kg$) refers to the corresponding embodied carbon coefficient of the construction materials.

3. RESULTS AND DISCUSSION

3.1 Mass Intensity

Table 1 illustrates the Mass Intensity (MI) values of reinforce concrete buildings which ranged from 1,595 – 2,252 kg/m^2, which meant that every square meter of building floor area consumed more than fifteen thousand of building materials. In addition, because of the relative complexity of a scientific laboratory room design, a greater amount of construction material was required compared to the other conventional rooms, accounting for Building A having the highest MI value. The proportion of MI on weighted average classified by building construction components and materials type revealed that SM component contributed the largest share with the major source of various concrete types used for the sole plate, foundation, structure and precast as illustrated in Fig. 1. This finding is in agreement with the data discoursed in previous studies [6,9].

With exception of Building A, high-rise buildings (Building B and D) exhibited more environmental-friendly performance in terms of resources depletion since such buildings required slightly less resources per functional unit than the low-rise building (Building C) even though the total consumption of resources was higher. Moreover, the MI value of the consumption of materials in DM component in Building C was almost twice more than that in the other buildings and was mainly influenced by the consumption of the cement group for wall finishing. Although the consumption of materials in the DM component is uncontrollable since it is heavily determined by individual satisfaction, to reduce the environmental impact, a loft design building, a building polished with neither ceramic tiles nor paint, was recommended as it could reduce the total MI by nearly 4% (Fig.1).

3.2 Embodied Carbon Intensity

Based on the weighted average with an exclusion of Building A, the embodied carbon intensity (ECI) of building construction materials in this study was 347 $kgCO_2/m^2$. Similar to the MI result, apart from Building A, Building C showed a higher value of ECI than the others (Building B and D). It could be concluded that, the smaller floor area is, the larger the amount of embodied carbon intensity presents. This finding is in disagreement with the research on the embodied carbon emission of office buildings in China, which concluded that buildings with a larger area, emitted more carbon emissions per unit area [10]. However, that study was focused on a comparison between multi-story building, high-rise building and super- high-rise building, where as this research was an investigation of small building and high-rise building. Accordingly, it might be implied that the height of a building makes a significant contribution to the global warming in a height-dependent range.

Table 1 Mass intensity (MI) and embodied carbon intensity (ECI) of major construction materials used in educational buildings

Materials	Building A		Building B		Building C		Building D	
	MI	ECI	MI	ECI	MI	ECI	MI	ECI
Structural Materials (SM)								
Group of Concrete	1,875.74	197.23	1,281.54	134.63	1,287.43	136.13	1,363.19	144.51
Sawnwood	124.86	1.90	72.79	1.11	80.57	1.23	79.87	1.22
Aggregate	11.13	0.02	44.49	0.08	4.39	0.01	3.81	0.01
Group of Steel	63.56	140.87	35.48	79.10	31.39	73.01	36.57	82.61
Sub-total	2,075	340	1,434	215	1,404	210	1,483	228
Decoration Materials (DM)								
Group of Cement	66.54	15.55	58.15	15.18	146.69	33.98	67.44	16.61
Brick	36.75	8.62	23.34	5.47	29.38	6.89	9.65	2.26
Aggregate	32.06	1.27	37.41	0.07	15.23	0.81	36.65	0.12
Ceramic Tile	4.15	1.55	10.70	4.00	63.47	23.71	21.12	7.89
Gypsum Fibreboard	13.20	9.90	8.17	6.13	3.79	2.85	4.24	3.18
Group of Steel	8.57	22.68	6.10	14.51	3.49	14.14	3.49	9.16
Sawnwood	1.99	0.03	-	-	-	-	0.92	0.13
Tap Water	4.63	0.00	4.77	0.00	3.07	0.00	5.52	0.00
Group of Paint	3.03	13.30	2.11	9.11	2.46	10.40	2.61	10.81
Aluminium	-	-	1.63	63.42	15.21	47.78	0.39	1.21
Insulation	0.60	2.58	-	-	8.60	20.92	-	-
PVC	1.09	2.07	0.62	1.89	2.74	5.21	0.99	1.88
Sub-total	173	78	155	120	294	167	153	53
Materials supplied for Ventilation and Air Condition (VA) system								
Copper	0.31	0.55	0.23	0.40	0.03	0.06	0.12	0.21
Steel	0.15	0.41	0.47	1.26	-	-	0.09	0.25
PVC	0.07	0.22	0.04	0.14	0.01	0.02	0.05	0.17
Polyurethane	0.02	0.10	0.02	0.10	-	0.01	0.01	0.06
Supply Air Inlet	n.d.	0.04	n.d.	0.04	n.d.	0.03	n.d.	0.01
Exhaust Air Outlet	n.d.	0.03	n.d.	0.17	n.d.	0.05	n.d.	0.02
Glass Fibre	-	-	0.04	0.10	-	-	-	-
Sub-total	1	1	1	2	0	0	0	1
Materials supplied for Sanitary and Fire Protection (SF) work								
Group of Steel	3.12	13.45	3.94	13.40	0.01	0.05	2.63	7.19
Glass fibre	-	-	0.58	1.41	0.45	1.10	0.21	0.52
Piping	0.21	0.67	0.13	0.38	0.48	1.54	1.48	4.70
Thermoforming	-	-	-	-	0.03	0.09	0.18	0.67
Sub-total	3	14	5	15	1	3	5	13
Total	2,252	433	1,595	352	1,699	380	1,641	295

Unit: Mass intensity (kg/m^2), Embodied Carbon Intensity ($kgCO_2/m^2$)

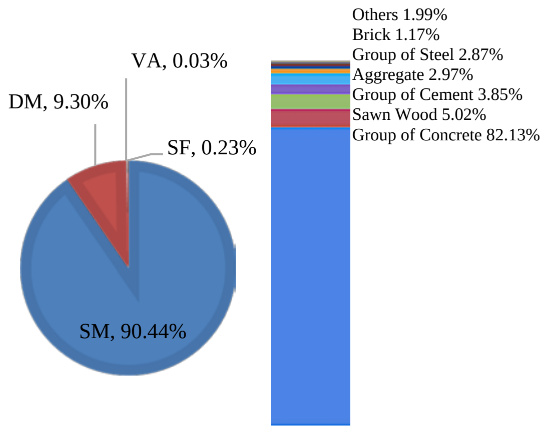

Fig.1 Proportion of mass in construction materials

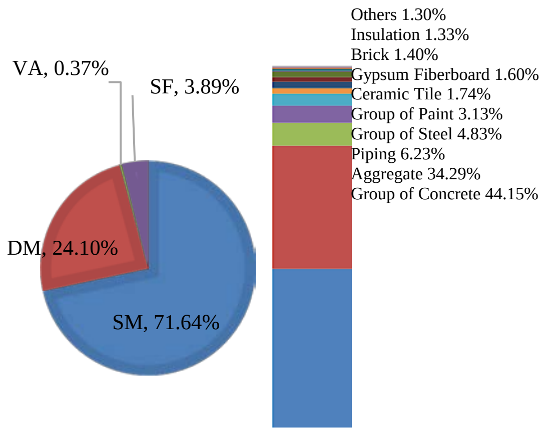

Fig. 2 Proportion of embodied carbon in construction materials

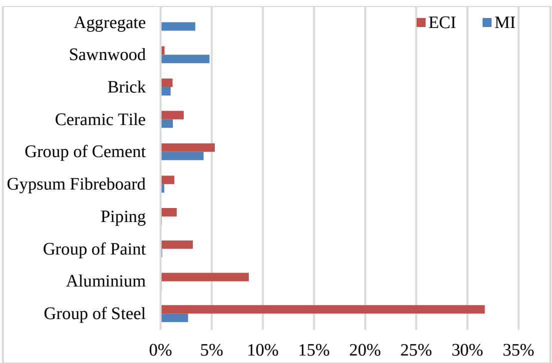

Fig. 3 Contribution of building materials to the mass and embodied carbon intensities

In addition, whilst a category of SM component was employed for more than 70% of the total embodied carbon emission, about one-fourth of such intensity was associated with the DM component. As presented in Fig 2, the two major materials that generated the greatest amount of carbon emission were a group of concrete (44%) and aggregate (34%). To reduce the carbon emission embodied from structural materials for new construction, the use of alternative building construction materials such as fly-ash or blast furnace slag is encouraged as a substitute for virgin cement, mortar, or concrete [11].

3.3 Relationship between the Mass and Embodied Carbon Intensity

Excluding the construction materials in a group of concrete which shared the highest contribution in both building material profile and in the embodied carbon content as mentioned above, Fig. 2 presents the contribution of ten building construction materials to the total MI and ECI.

There were three kinds of relationship among the contribution of materials to both variables. Firstly, high consumption materials with a high CO_2 emission, similar to the concrete group, was found at a high contribution in the group of cement and ceramic tile for both material mass and embodied carbon. Secondly, high consumption materials with a low CO_2 emission, such as sawn wood and aggregate, contributed to the total mass (3-4%) with an insignificant contribution to the embodied carbon (< 0.4%). Lastly, low consumption materials with a high CO_2 emission, due to their higher embodied carbon efficiencies, such as steel, brick, gypsum fiberboard, aluminium, paint, and piping, even though such materials were consumed at a low level in the construction process, they contributed a relatively large amount of carbon emission.

Therefore, alternatives for alleviating global warming through building sector should involve either high carbon emitting materials or mass materials. Based on the results of this study, buildings with reinforce concrete structure should focus on six materials namely concrete, steel, aluminium, cement, paint, and ceramic tiles since the contribution of such materials to the carbon emission accounted for 94% of the total embodied carbon. To roughly estimate the building coefficient, the specific carbon emission of building based on a reinforce concrete structure in Thailand was 0.198 $kgCO_2$/kg of material mass.

3.4 Comparison of Embodied Carbon Intensity with Other Studies

Comparison of ECI obtained from this study with the previous findings is presented in Table 2. Based on the same building typology, it was found that the ECI of this study was lower than the other cases. This might be because of the new innovations and advances in technology that have been developed occasionally from the past and also the impact of the greater total floor area that resulted in a decreased embodied carbon emission. However, considering the concept of a zero emission building (ZEB), it could be implied that to move towards a low carbon society, all new building constructions should be designed based on such themes since the building will emit zero emission during the operation phase whilst the contribution to the carbon profile during the construction phase will be compromised with the benefits gained by the utilization of building waste after its end-of-life stage.

3.5 Alternative Insulation Materials for Improving the Environmental Performance of Existing Building

For improving the existing building, the energy efficiency performance was mainly focused on and an energy simulation was introduced to anticipate the changes in energy consumption in building after implementation. Since more than half of the total energy used in building in tropical countries is consumed by the cooling system, various kinds of external wall insulation were selected to examine an amount of energy-related emissions that would be reduced and to identify the best solution for optimizing energy-related emissions throughout a building service life of 50 years. In this study, Building A – the highest ECI building – was selected to simulate energy use through EnergyPlus 8.8.0 model.

The results revealed that, if implemented, all external wall insulation types could reduce the energy required during the building use phase since they all help reduce the heat gain into the building from the outside to a broadly similar level. The best option of external wall insulation in reducing carbon emission over the entire building service life was cellulose followed by glass wool and polyurethane. However, aerogel insulation showed no gain in the reduction potential because of its high embodied carbon coefficient, as demonstrated in Table 3.

For the entire building service life (50year), installation of cellulose insulation could reduce about 1,164 tCO_2e due to the energy saving during the use phase. This energy saving can compensate for the increased amount of embodied carbon in the building from the increased material (insulation) consumed, where the payback period of carbon offset was 1.4 years/10 years of insulation replacement.

Table 2 Embodied carbon emissions of various educational buildings

No.	Year	Location	Structure Type	No. of floor	Total Floor area (m^2)	ECI ($kgCO_2e/m^2$)	Ref.
1	2003	Michigan	Reinforced concrete	6	7,300	554.79	[12]
2	2011	Catalonia	Reinforced concrete	1	3,168	616.67	[13]
3	2015	Korea	Reinforced concrete	-	-	419.74[a]	[14]
4	2018	Sri Lanka	Reinforced concrete	7	5,967	490.93	[15]
5	2018	Norway[b]	Reinforced concrete	2	1,140	384.60	[16]
				5	26,356	418.20	
6	2018	Bangkok	Reinforced concrete	2	3,225	379.90	This study
			Reinforced concrete	13	21,627	352.11	
			Reinforced concrete	17	31,500	295.39	

[a] Data of 7 educational buildings on average in Suwon city, Korea.
[b] Demonstration of zero emission building (ZEB) case studies

Table 3 Properties of base case and alternative external wall insulation materials

Indicator \ Insulation Material[a]	Unit	Base Case	Cellulose	Aerogel	Poly urethane	Glass Wool
Embodied carbon co-efficient [17]	$kgCO_2/kg$	-	4.60	47.3	22.9	5.60
Embodied carbon of insulation[b]	$kgCO_2$	-	32,324	332,377	160,918	39,351
Embodied carbon of entire building[c]	tCO_2/BSL	7,000	7,162	8,663	7,805	7,198
Energy consumed in use phase	MWh/year	2,926	2,885	2,884	2,886	2,885
Reduction due to energy saving	$kgCO_2$/year	-	23,284	23,763	23,136	23,588
Energy-related emission[d]	tCO_2/BSL	82,874	81,710	81,686	81,717	81,695
Emissions reduction compared to Base case	tCO_2/BSL	-	1,002	-475	352	981

[a]Assumed all insulation lifetime of 10 years.
[b]Wall area for insulation installation in entire building is 7,027 m^2 and wall insulation thickness is 100 mm for all cases, except aerogel (50 mm)
[c]Building service life (BSL) is 50 years, thus 5 sets of insulation were installed throughout BSL.

[d]CO_2 emission due to electricity use in Thailand is 0.5664 $kgCO_2$/kWh [18]

4. CONCLUSION

As the global trend moves towards nearly zero carbon building, this study aimed at quantifying the amount of embodied carbon in construction materials and identifying the key materials effecting the proportion of embodied carbon intensity in order to propose alternative solutions for minimizing the environmental impacts throughout a building service life. Buildings located in a Thai academic institute were used to demonstrate the intensities of materials mass and embodied carbon. The results illustrated that, on weighted average, the intensities of mass and embodied carbon in building construction materials were 1,627 kg/m^2 and 322 $kgCO_2/m^2$. In addition, in term of the building size, high-rise building was found to contribute less to both intensities than low-rise building. To roughly estimate the building coefficient, the specific carbon emission of an educational building in Thailand was 0.198 $kgCO_2$/kg of material mass.

The findings also indicated that the structural material component contributed the highest share to either the mass or embodied carbon intensities, followed by the decoration materials component, the materials supplied for sanitary and fire protection work and for ventilation and air condition system respectively. Moreover, in order to mitigate the embodied carbon of a building, two group of materials that should be focused on were a group of high embodied carbon efficient materials and a group of materials used in a large amount.

To improve the existing building, a solution for reducing the energy consumption in the cooling system was investigated as this uses the highest loads of energy. The result of energy simulation by applying four different external wall insulations revealed that even though all four insulations provided a similar benefit in term of a reduced energy consumption during the operation phase compared to the base case, aerogel insulation failed to improve the building performance over the entire building service life of 50 years because of its high embodied carbon coefficient.

The characteristic of all buildings in this study were very similar to most typical buildings in Thailand since the material used for foundation and structure was based on reinforce concrete and the envelope pattern was an opaque wall constructed from brick. The findings of this study, therefore, could be widely applied to other buildings. The initiative of reducing carbon emissions in the building sector on either loft style building or on zero emission building could lead to sustainable consumption and production in Thailand, enabling the country to move towards a low carbon society successfully as planned.

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