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Incorporating environmental evaluation and thermal properties of concrete mix designs

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Abstract

One of the main challenges in sustainable design of buildings is to improve the energy efficiency of the building during its lifetime along with reducing the environmental impact of the design. Recent advances in concrete technology offer lower embodied emission through the application of supplementary cementitious materials and recycled aggregates. There are also improvements to thermal properties with the application of admixtures. However, the relationships between the environmental impact (Cradle to Gate) and thermal performance of concrete mix designs have not been researched adequately. The Green House Gas (GHG) emissions associated with each individual concrete component and its production need to be considered with greater refinement. This study correlates the impacts of selecting a concrete mix design in terms of CO_2-e with resulting thermal conductivity and density at the design stage of buildings. This paper examines 90 concrete mix designs from published literature to identify their embodied emissions and thermal conductivity in order to discuss the relationship between low embodied carbon dioxide equivalents (CO_2-e) emission alternatives and thermal conductivity. The embodied CO_2-e of a variety concrete mix designs were quantified by compiling embodied CO_2-e coefficient for each individual component in the concrete. The results show the variation in embodied CO2-e and thermal conductivity of concrete mixes. The application of readily available supplementary cementitious material can reduce embodied CO_2-e (kg CO_2-e) by up to 16% in comparison with general practice. Furthermore, the thermal conductivity of concrete mix is influenced by changing the density of aggregates and the proportion of cementitious materials. In completing this work the results obtained from the study are compared with six different inventory databases: ICE (Hammond et al., 2011), Crawford (2011), Alcon (2003), eTool (2014), BPIC (2014) and AusLCI (2013). The comparison identifies some inconsistencies in calculation of embodied CO_2-e across the different databases. This is attributed to variation in embodied CO_2-e coefficients and lack of in-depth consideration of the detailed properties of each individual concrete mix design.

Keywords

mix, concrete, designs, properties, environmental, evaluation, thermal, incorporating

Disciplines

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Incorporating environmental evaluation and thermal properties of concrete mix designs

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Abstract

One of the main challenges in sustainable design of buildings is to improve the energy efficiency of the building during its lifetime along with reducing the environmental impact of the design. Recent advances in concrete technology offer lower embodied emission through the application of supplementary cementitious materials and recycled aggregates. There are also improvements to thermal properties with the application of admixtures. However, the relationships between the environmental impact (Cradle to Gate) and thermal performance of concrete mix designs have not been researched adequately. The Green House Gas (GHG) emissions associated with each individual concrete component and its production need to be considered with greater refinement. This study correlates the impacts of selecting a concrete mix design in terms of CO2-e with resulting thermal conductivity and density at the design stage of buildings. This paper examines 90 concrete mix designs from published literature to identify their embodied emissions and thermal conductivity in order to discuss the relationship between low embodied carbon dioxide equivalents (CO_2-e) emission alternatives and thermal conductivity. The embodied CO_2-e of a variety concrete mix designs were quantified by compiling embodied CO_2-e coefficient for each individual component in the concrete. The results show the variation in embodied CO_2-e and thermal conductivity of concrete mixes. The application of readily available supplementary cementitious material can reduce embodied CO_2-e (kg CO_2-e) by up to 16% in comparison with general practice. Furthermore, the thermal conductivity of concrete mix is influenced by changing the density of aggregates and the proportion of cementitious materials. In completing this work the results obtained from the study are compared with six different inventory databases: ICE [1], Crawford [2], Alcon [3], eTool [4], BPIC [5] and AusLCI [6]. The comparison identifies some inconsistencies in calculation of embodied CO_2-e across the different databases. This is attributed to variation in embodied CO_2-e coefficients and lack of in-depth consideration of the detailed properties of each individual concrete mix design.

Keyword: Concrete mix design, Embodied emission, Thermal conductivity, GHG, CO_2-e

1-Introduction

Concrete is the most widely used construction material in the building industry and consumes the second highest amount of natural resources [7]. The main constituents of general purpose concrete are cement, water and aggregates. The most carbon intensive components in manufacturing concrete are cement and aggregates. A report released by the United States Geological Survey shows that global cement production increased by 100 million tonnes in one year to a total of 4.18 billion tonne in 2014 [8]. The American Portland Cement Association (PCA) has estimated this cement consumption trend will continue to increase into the future [9].

Concrete is a popular material because it has excellent mechanical and durability properties. It is adaptable, relatively fire resistant and generally available and affordable. Concrete has the ability to absorb and retain energy for a considerable period of time. This action reduces energy consumption by transferring heat in a natural daily cycle through the structural components (thermal mass) of the building. The mass components reduce the temperature fluctuations in building spaces and can therefore reduce the associated peak heating or cooling loads [10].

Through its high thermal mass, a concrete slab can often absorb heat during the day and release it back to the room at night. The relatively high specific heat of solid concrete makes it attractive as a passive thermal store. An appropriate design of concrete mix can offer this thermal performance benefits, leading to a reduction in heating and cooling energy consumption in buildings [11, 12].

This situation raises a question about how best to design a concrete mix with respect to strength, thermal properties, environmental impact and CO_2-e intensity of concrete. The objective of this paper is to identify the environmental impact and thermal performance of different concrete mix designs by considering both the embodied CO_2-e and the impact on the thermal properties of concrete.

1-1 Thermal performance of concrete

Concrete is one of several building materials that possess high thermal properties. In cold seasons, high thermal mass building elements that contain concrete such as walls and floor slabs, absorb radiant heat from the sun during the day and release it gradually back into the system (space) during night when outside temperatures drop [13]. The distinct benefit of high thermal mass is to moderate changes in peak load of energy requirements due to fluctuations between inside and outside temperatures. High thermal mass causes a time lag between internal and external temperatures (Figure 1). It also stores heat which dampens the fluctuation between peaks. This often results in improved thermal comfort and less energy demand for heating and cooling[13]. Beside thermal mass, thermal properties of concrete mix design such as conductivity have a considerable influence on passive heating design strategy. An optimum design of concrete mix could either reduce escape of passive heating before being absorbed or re-released a stored heat before the colder night [14].

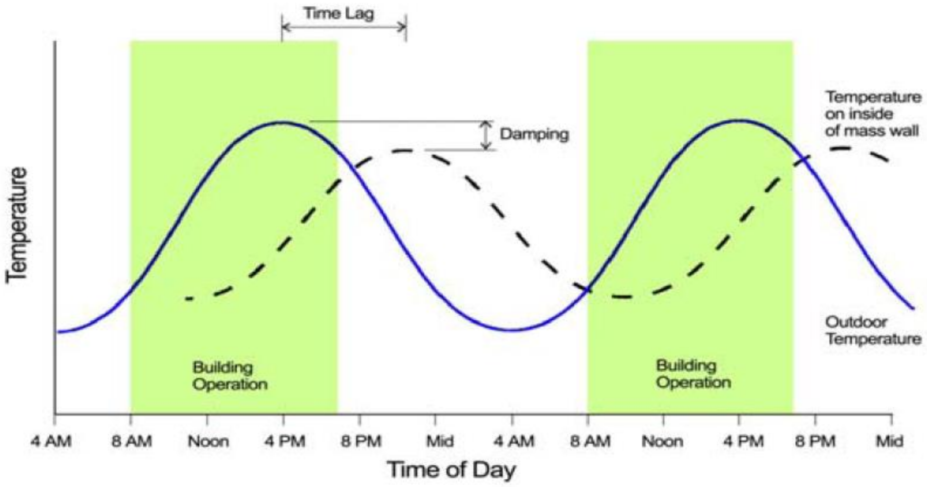

Figure 1 Damping and lag effect of thermal mass [13]

Thermal conductivity of concrete mix designs is influenced by the thermal properties of the ingredients such as cement, aggregates and the existing moisture [15]. Thermal conductivity of concrete is dependent on the type of aggregates used in the concrete mixture. Some published construction properties databases associate thermal conductivity to concrete density, for example ACI122R [15] and CIBSE [16]. Therefore, it is possible to take into the account some thermal properties of concrete mixes at the initial stage of the structural design of buildings. This study quantifies the thermal conductivity for different concrete mix designs.

1-2 Environmental aspects of Concrete

The basic constituents of concrete are binder (cementitious materials), coarse and fine aggregates (or inactive mineral filler) and water. The properties of these materials, their combination, the effects of various admixtures and how it is handled during construction determine the properties of the in-situ concrete.

The major source of greenhouse emissions during the production of concrete is the Portland cement. The cement sector was responsible for 2,823 million metric tons (Mt) of embodied CO_2-e in 2010 [17]. This related to almost 9% of global CO_2-e emissions from burning of fossil fuels in 2010 [17]. Traditional methods to respond to this issue are the development of energy efficient cement production plants through improved technology, changes to energy sources used and the application of substitutes for clinker by using waste materials such as fly ash and ground granulated blast furnace slag [18-21].

The concrete industry is addressing some of the worries about environmental issues by supplementing or replacing the use of cement and other components that are associated with high embodied CO_2-e. Several researchers have studied the possibility of cement replacement in the concrete with recycled materials [22-24]. The use of alternative cementitious materials remains the main path to the reduction of embodied CO_2-e in the concrete industry [25]. Wimpenny [26] conducted a study in low CO_2-e alternatives to concrete by exploring strategies being adopted and developed in 12 countries around the world. The results have been classified into seven groups as shown in Table 1.

Table 1 embodied CO_2-e for cementitious materials [26]

Group	Example	Suggested quantities	embodied CO_2-e	References
Alternative cementitious materials	Fly ash	40%	Medium	[26, 27]
	Slag	80%	Low	
	Silica fume	10%	Low	
	Metakaolin	10%	Very high	
	Municipal solid waste incinerator ash (MSWIA)	-----	Medium	
Non-Portland cement binders	Geopolymer	-----	Low	[28, 29]
	Calcium sulphate based		Low	
	Calcium sulfoaluminate		High	
	Magnesite based		High	
Low cement concrete	Lean Concrete	-----	Medium	[26]
Ultra-high strength	Fibre reinforced superplasticiser silica fume	-----	Medium	[26]

concrete	concrete (FRSSFC)			
Changes in Portland cement manufacture	Oxygen enrichment of kiln atmosphere to enhance burning	-----	Medium	[28]
	Belite cements Alinite and Fluoralinite cement Portland limestone cement	-----	Very high --------- ---------	
Alternative binder types	Bituminous based materials (Agent C)	-----	Very low	[26]
Carbon capture	Sequestering carbon from the kiln capturing carbon in the concrete, e.g. Hemp (Lime based binder and hemp)	-----	Very low	[29]

The most commonly used alternative cementitious materials are Ground Granulated Blast Furnace Slag (GGBFS) and coal combustion fly ash. GGBFS is obtained as a by-product of iron and steel making and fly ash is obtained as a by-product of burning coal mainly for electricity generation. These cementitious materials are used to replace a portion of the cement in the concrete mix design. The production process of fly ash and GGBFS involve less greenhouse gas emissions compared with ordinary Portland cement [30].

Fly ash is a widely available material which, if not used in concrete, is an industrial waste with serious disposal problems. Worldwide, the majority of annual production of fly ash is disposed of as waste material in ash dams or in a landfill [31]. In Australia, about 20% of fly ash produced in coal-fired power stations is used in construction industry [32]. The Australian Standard, AS3582.1, sets specific requirements for fly ash and has classified it into three grades (fine, medium and coarse)[33]. If the physical properties of the fly ash do not comply with the AS3582.1 Standard requirements it cannot be used as a supplementary material in the cement and concrete industry [31]. The proportion of fly ash in blended cement typically changed from 15% to 30% and for some particular applications, this amount can be increased to 50% to 60% [34, 35]. The positive contribution of fly ash for reducing concrete embodied CO_2-e has been quantified to be up to 44% when it substitutes 40% of Portland cement in a typical concrete mix design [36]. However, it should be noted that the decrease in the use of coal might also have a negative impact on supply of fly ash [37].

Other supplementary materials such as GGBFS can also be used to replace Portland cement in concrete. Substituting a portion of Portland cement with GGBFS can substantially reduce the negative environmental impact of concrete [38]. Fly ash and GGBFS can be added separately to the concrete mix. However, in comparison to the quantities of fly ash, the availability of GGBFS is limited. The worldwide production of GGBFS is only 25 million tonnes per year [39]. The proportion of GGFS in concrete typically varies from 40% to 60% of the overall amount of blended cement [40].

Other supplementary cementitious materials are silica fume, rice husk ash, and recycled ground glass. The availability of these materials are limited compared with the fly ash so their costs are relatively higher [41].

Geopolymer concrete is another alternative concrete in which an alkali activated aluminosilicate material is used as a replacement of traditional cement binders[42]. Geopolymers generally have a lower embodied CO_2-e than cement but are currently significantly more expensive to produce [43].

Meanwhile, it has to be mentioned that there are some barriers to implementation of the new type of materials to achieve lightweight and/or geopolymer concrete. These barriers include regulatory, technical, supply chain and cost of geopolymer concrete [44-46]. There are currently several research programs that aim to remove the existing barriers for a wider application of geopolymer and/or lightweight concretes.

Aggregate characteristics have significant effects on physical properties of concrete (grade, moisture absorption, thermal conductivity, etc.). Aggregates have also potential to be reused as raw materials in the concrete at the end of life [47]. The choice of aggregates is very much related to a local supply chain. Quarries with adequate natural aggregates are being depleted in some regions and countries and the tendency to use of more crushed and manufactured aggregates is increasing [48]. From an emissions point of view, a distinction must be made between natural and crushed aggregate. Natural aggregates, such as sand and gravel, are the results of weathering and erosion and do not require any processing other than collection and transportation. Crushed aggregates, such as manufactured sand, are mined from quarries and require mechanical crushing. Flower and Sanjayan [49] showed that granite/hornfels as a crushed aggregate have GHG emissions of 45.9 kg CO_2–e/tonne and basalt as a natural aggregates have GHG emissions of 35.7 kg CO_2-e/tonne [49] .

The water demand for concrete depends on the type of mix design and use of plasticising additives. The use of water in concrete leads to minimal embodied CO_2-e, which leaves cement, coarse and fine aggregates, GGBFS and fly ash as the main material contributors to the environmental impact.

Previous studies into the environmental impact of the production of cementitious materials and aggregates have already yielded several estimates of the embodied CO_2-e per tonne of concrete [25, 39, 49, 50]. The embodied CO_2-e are calculated by multiplying embodied CO_2-e coefficients from proposed databases [1-4] for each grade of concrete by the quantity of concrete. This method suffers from a lack of comprehensive attention into the individual concrete components. The GHG emissions associated with each individual concrete component need to be sufficiently investigated [49]. Furthermore, the relationship between embodied CO_2-e, thermal conductivity and alternative cementitious materials has not been sufficiently determined. The main objective of this study was to identify the relationship between low embodied CO_2-e and low thermal conductivity for a large number of concrete mix designs. This paper analyses different concrete mix designs and compares the results when sourcing inputs from a number of available inventory databases.

2-Methodology

2-1 Materials and Mix designs

This study investigates 90 different concrete mix designs. The two primary performance variables are the grade and density of the concrete. The concrete mix designs were collected from 8 published journal papers and databases [51-59]. These mix designs represent some conventional (normal weight) and some advanced methods of concrete admixture [52, 54, 56, 57] that gives lightweight and ultra-lightweight concrete. Table 2 summarizes the concrete grades and the 90 mix cases of the different batches of concrete that were analysed in this paper. The reason to include novel forms of concrete admixture (such as Mix 27-41) in the paper was to point out their thermal properties and environmental impacts which have not been covered in the mainstream of studies. The concrete grades range from 28 MPa to 87 MPa. The detailed concrete mix designs and ingredients are shown in Appendix 1.

Table 2 Summary of concrete batches

Mix No.	Concrete Grade (MPa)	Composition of mix				Source
		Binder	Aggregates	Admixture	Water	
Mix 1-3	32,40	Portland cement, GGBFS, fly ash	natural aggregates, recycled aggregates, manufactured sand, fine natural river sand	Water reducing	Potable water, Reclaimed water	CCAA [51]
Mix 4-9	31.6-42.7	Portland cement	natural aggregates, manufactured sand, Lightweight aggregate*, Furnace bottom ash	Water reducing	Potable water	Zhang and Poon [52]
Mix 10-26	32,35,40	Portland cement, fly ash	natural aggregates and manufactured sand	------	Potable water	Berndt [53]
Mix 27-41	33-69.4	Portland cement, cenosphere, silica fume	natural aggregates and manufactured sand	Superplasticiser , shrinkage reduction, Viscosity modify agent, Polyethylene fibers, Silane	Potable water	Wu, Wang, Monteiro and Zhang [54]
Mix 42-57	38-55	Portland cement, GGBFS, fly ash, silica fume	natural aggregates, recycled aggregates,	------	Potable water	Damdelen, Georgopoulos and Limbachiya [55]
Mix 58-69	23-43.9	Portland cement, fly ash	natural aggregates, Lightweight aggregate*, Glass bubble	------	Potable water	Yun, Jeong, Han and Youm [56]
Mix 70-75	33.6-48.6	Portland cement,	natural aggregates	------	Potable water	Marinkovic, Radonjanin, Malesev and Ignjatovic [57]
Mix 76-79	41.5-44.2	Portland cement,	natural aggregates, recycled aggregates,	------	Potable water	Tošić, Marinković, Dašić and Stanić [58]
Mix 80-90	32	Portland cement, GGBFS, fly ash,	natural aggregates	------	Potable water	O'Moore and O'Brien [59]

*Lightweight aggregate consists of manufactured aggregate (shale, slate and clay) and Glass bubble.

This study considers each individual concrete component in order to estimate the equivalent greenhouse emissions and thermal conductivity of the mixed design. The embodied CO_2-e for a variety of concrete mix designs was quantified by collecting relative embodied CO_2-e coefficients for each individual concrete component from existing studies [49, 60-62].

The estimated emission coefficient for each material was multiplied by the respective quantity of the material, and the resulting embodied CO_2-e was summed up for each mix design. The comparison includes the results obtained from this study against six different embodied CO_2-e data inventories, namely; ICE [1], Crawford [2], Alcorn [3], eTool [4] and BPIC (an average industrial practice database) [5] and AusLCI [6]. As the study undertaken by Crawford covers embodied energy rather than embodied CO_2-e, a conservative coefficient of 10% (based on the ratio used in eTool database) was used to convert data into embodied CO_2-e (kg CO_2-e). Linear interpolation was used for Crawford databases to estimate the coefficient for the embodied CO_2-e of all grades of concrete that are proposed in the concrete mix data of this study. For the ICE database, linear interpolation was used to estimate the embodied CO_2-e coefficient when different percentages of cement were replaced with slag and/or fly ash. Calculation of the thermal conductivity of each mix design follows the ACI122R [15] guideline. ACI122R proposes that the thermal conductivity of a concrete mixture is based on the individual material properties comprising the mixture (aggregate) and the oven dry density of the mixture (kg/m^3).

2-2 Embodied Carbon Dioxide Equivalent Emissions

The emission factors for binders, aggregates and admixtures were obtained from Flower and Sanjayan [49] and were based on the Australian Green house office factors and method workbook [63]. The emission factor for recycled aggregates was collected from ARRB Group report [61]. The embodied emission associated with manufactured aggregates was considered the same as the natural aggregates in regards to the upstream stage of the production process [64]. The emission associated with potable water and captured water was based on the results of Rouwette [60]. The boundary of the system for calculating the total embodied CO_2-e is depicted in Figure 2. This study considered the embodied CO_2-e associated with concrete and concrete materials from cradle to gate. This system includes all the steps from extraction of raw materials, transport to the concrete plant, mixing and production of concrete by considering relevant consumed energy (Diesel fuel, LPG fuel and electricity). The process of transportation and placement of concrete is excluded in this study. Table 3 summarizes the final embodied CO_2-e coefficients that are related to individual concrete components.

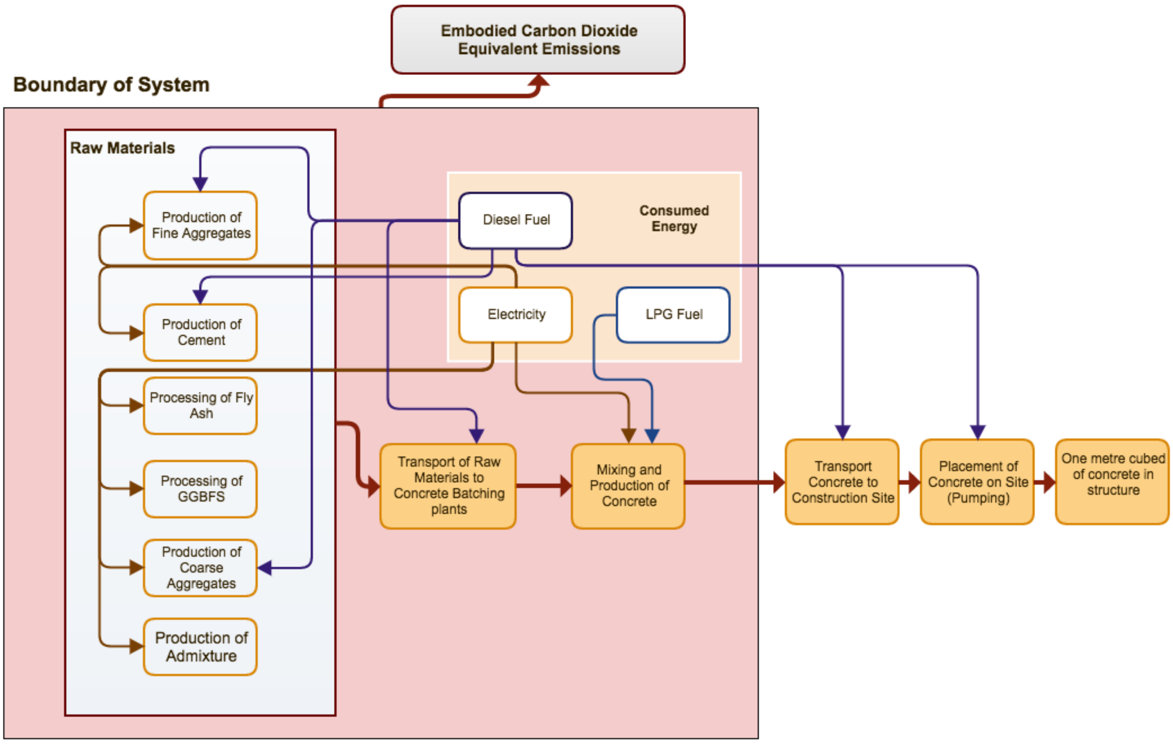

Figure 2 Concrete embodied CO2-e system diagram

Table 3 Final embodied CO2-e coefficients

Activity	Material	Emissions coefficient	References
Binder (t CO2-e/ tonne)	Type of Portland cement	0.820	[49, 62]
	Ground Slag ; Ground Granulated blast furnace	0.143	
	Fly ash or pulverized fuel ash	0.027	
	Furnace bottom ash	0.027	
	cenosphere	0.027	
Aggregates **(t CO_2-e/ tonne)**	Natural aggregates	0.0459	[49, 61]
	Recycled aggregates	0.004	
	Manufactured Sand	0.0139	
	Fine natural river sand	0.0139	
Admixture **(t CO_2-e/ L)**	Water reducing admixture	2.2×10^{-6}	[49]
	Superplasticiser	5.2×10^{-6}	
Water **(t CO_2-e/ tonne)**	Potable water	7×10^{-4}	[60]
	Captured/ Reclaimed water	7×10^{-5}	

3-Results and discussion

3-1 Embodied emissions

The resulting cradle to gate life cycle embodied CO_2-e of the 90 concrete mixtures are shown in Figure 3. The quantities of embodied CO_2-e relate to 1 m^3 of concrete. As the results in Figure 3 show, the amount of embodied CO_2-e was influenced by variations in the concrete mixture.

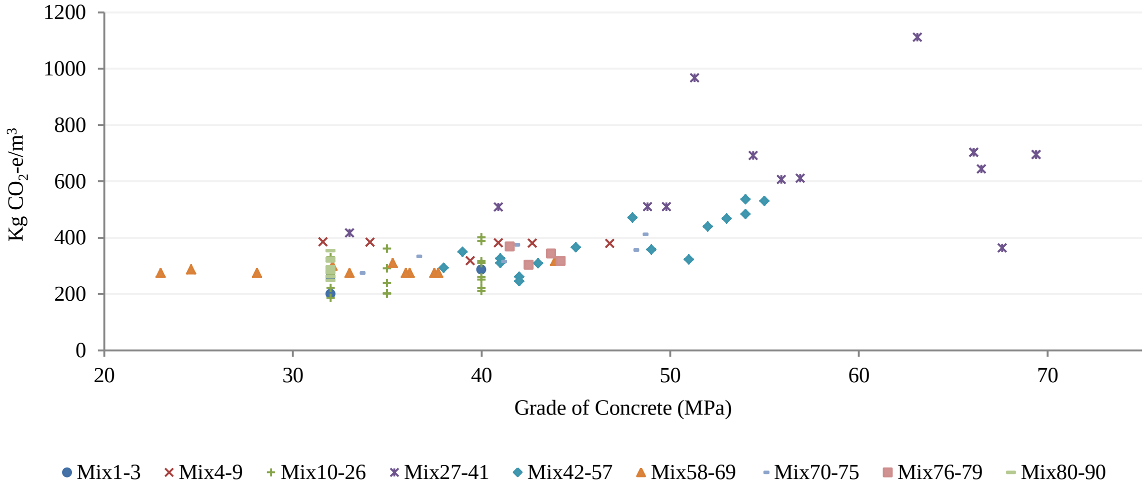

Figure 3 Embodied CO_2-e for different grades of Concrete

Figure 4 illustrates the variation of embodied CO_2-e per m^3 of concrete for two selected groups of concrete (32-35 MPa and 38-42 MPa). The data was categorised into the common standardised grades of 32 and 40 MPa due to variability in the expected concrete strength [65] and also because these two categories are popular in the structural design of buildings. The graphically depicted embodied CO_2-e results show the variation along with different mix designs for the two selected groups. The statistical distribution of data displays interquartile ranges between 72.9 and 103.1 Kg CO_2-e/m^3 for group 32-35MPa and 38-42 MPa respectively (Figure 4).

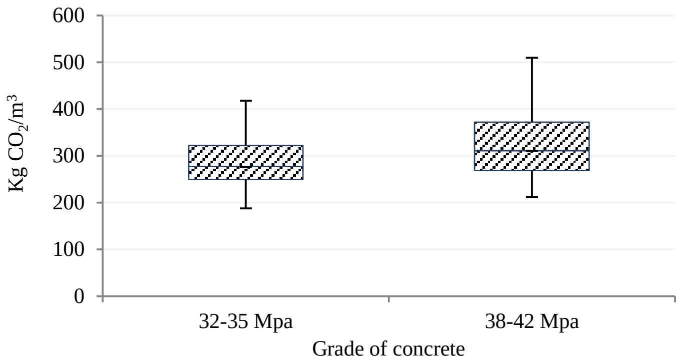

Figure 4 Variation in embodied CO_2-e for 32 MPa and 40 MPa concrete mixes

For a grade of 32-35MPa concrete the embodied CO_2-e range from 187.2 to 417.5 kg CO_2-e/m^3 by a central tendency of 277 kg CO_2-e/m^3. The detailed results in Figure 5 shows mix number 13 and mix number 32 achieved the lowest and highest embodied CO_2-e respectively when compared with the other mixes. For mix design number 13, 65% of binder was blast furnace slag and 35% was general Portland cement. The resulted mix with the lowest emissions (mix design number 32) includes 58% general Portland cement, 37% cenosphere and 5% silica fume.

For group 38-42 MPa, the embodied CO_2-e was calculated to vary from 211 to 509 kg CO_2-e/m^3 by median value of 311 kg CO_2-e/m^3 as shown in Figure 6. Mix number 22 and 36 produced the lowest and highest amount of embodied CO_2-e per m^3 of concrete, respectively. Mix 22 binder contains 35% Portland cement and 65% blast furnace slag. Mix 36 consisted of 55% Portland cement, 40% cenosphere and 5% silica fume.

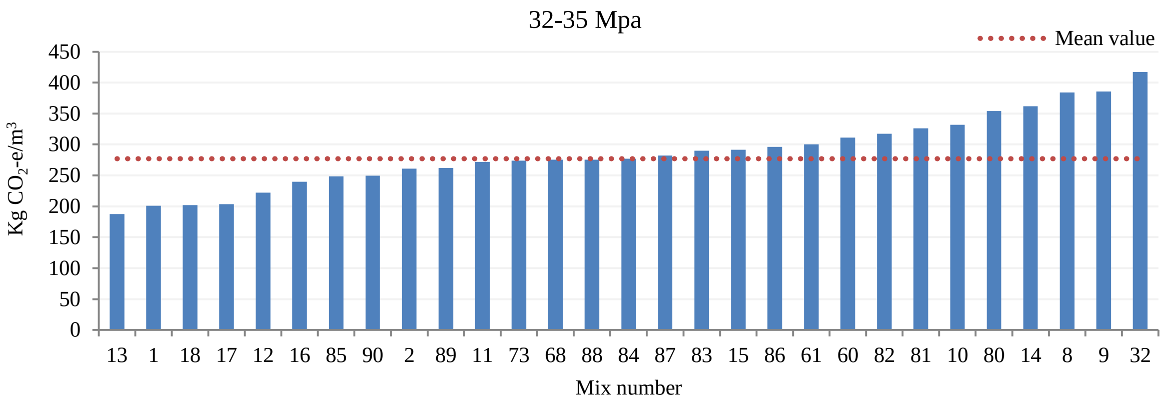

Figure 5 Embodied CO2-e for 32-35 MPa

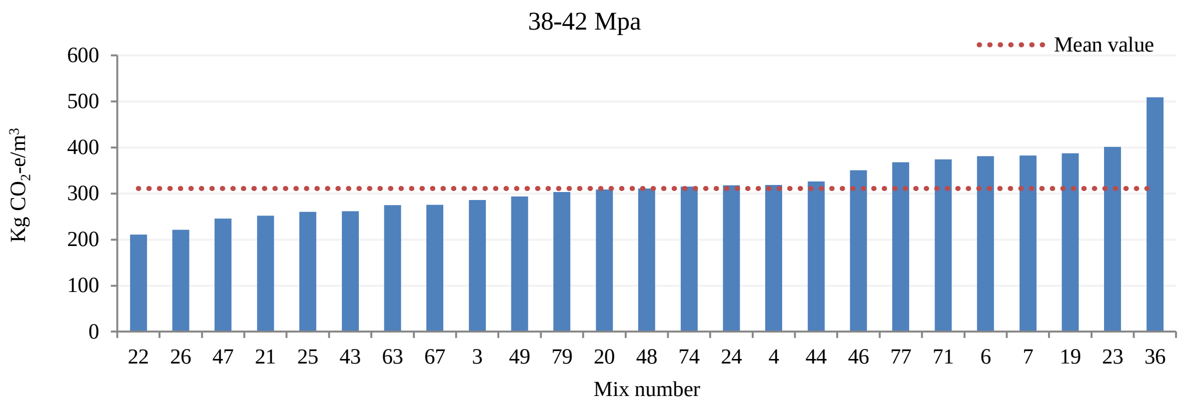

Figure 6 Embodied CO2-e for 38-42 MPa concrete

Various methods have been proposed for reducing the embodied CO_2-e of Portland cement [43, 66-68]. For instance, the efficiency of making cement can be improved by reducing the proportion of clinker and replacing it by ground granulated blast furnace slag (GGBFS). Also, supplementary cementitious and pozzolanic materials, such as GGBFS, fly ash, silica fume, rice husk ash and metakaolin have been considered as a replacement of Portland cement [43, 69, 70]. This study quantifies the effect from replacing portions of Portland cement with fly ash and GGBFS. The results show that concrete mixes with fly ash have 8% to 30% less embodied CO_2-e compared to the mix with 100% Portland cement (mix 80-85). GGBFS was found to be capable of reducing concrete embodied CO_2-e by 15.5% in the concrete mixture (mix 86-90). It should also be mentioned that the emissions associated with the production of concrete are related to parameters such as the availability of raw materials in the region and as the amount of emissions produced during transportation. This study considered the embodied CO_2-e associated with concrete and concrete materials from cradle to gate and such parameters (transportation, region, etc.) were not taken into account.

3-2 Variations in embodied CO_2-e coefficient

The estimated embodied CO_2-e emissions for the two selected concrete grade groups were compared between the Crawford, ICE, Alcorn, eTool, BPIC and AusLCI inventory embodied CO_2-e databases. Figure 7 and Figure 8 illustrate the embodied CO_2-e across mixture designs for grade 32-35 MPa and 38-42 MPa.

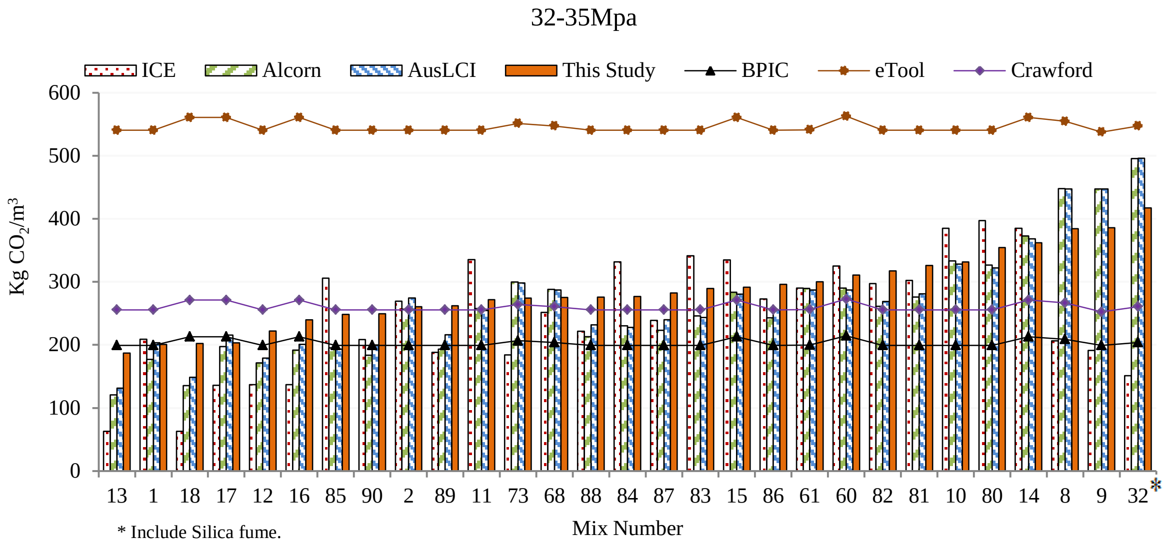

Figure 7 Embodied CO_2-e across inventory databases for 32 MPa concrete

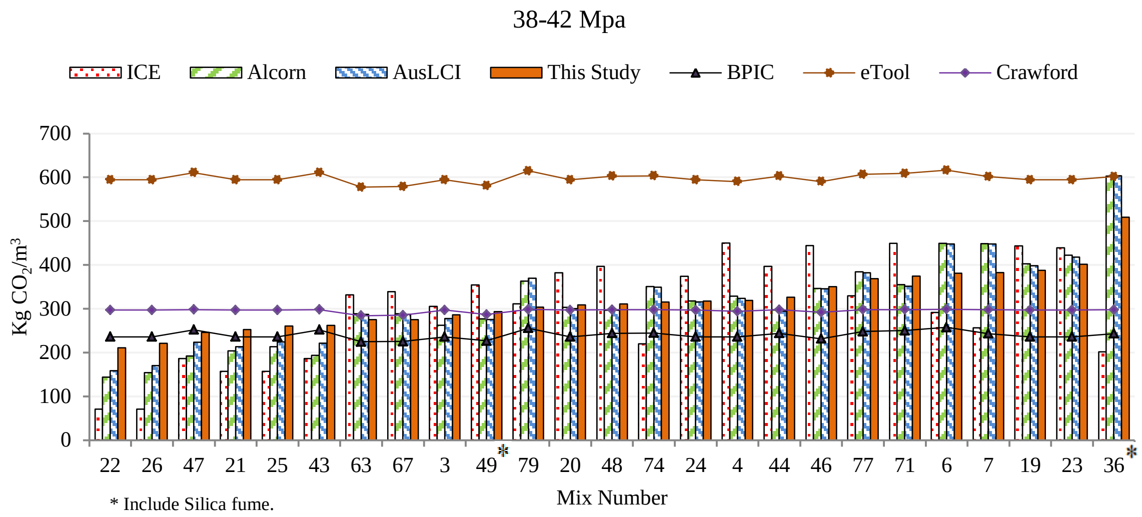

Figure 8 Embodied CO_2-e across inventory databases for 40 MPa concrete

The comparison shows that the amount of embodied CO_2-e for grade 32 MPa can vary significantly from 62.8 to 495.9 kg CO_2-e/m^3 of concrete depending on the type of mix design and inventory database. Similarly, significantly different embodied CO_2-e for grade 40MPa concrete were obtained (from 70.3 to 616.3 kg CO_2-e/m^3 of concrete) across the different mix designs and databases. The resulting embodied CO_2-e based on Crawford, eTool and BPIC databases have treated concrete as one specific product and have proposed an individual coefficient for each grade of concrete regardless of the mix of ingredients. The minor changes (less than 4%) in the results of each database including BPIC, eTool and Crawford is due to the changes in density of concrete mix designs and the embodied CO_2-e coefficients that are a function of concrete density. On the other hand, the concrete mix comparison results from the ICE database and this study (using the coefficients of Table 3) show that mix designs 13 for 32 MPa concrete and 22 for 40 MPa concrete have the lowest embodied CO_2-e. This stems from replacing 65% of cement with blast furnace slag. As expected, the maximum embodied CO_2-e was recorded for mix 32 and mix 36 for group 32 and 40 MPa, respectively in which no supplementary cementitious materials were used (i.e. 100% Portland cement was used).

From the data in Figure 7 and 8, it is apparent that the results based on AusLCI and Alcorn analysis represent less than 4% difference and both databases are capable to illustrate variations between mix designs. Similar to the results of this study, the highest embodied energy was recorded for the mix designs 36 and 32 for a grade of 32 and 40 MPa, respectively. The lowest embodied emission was archived through the mix designs 13 and 22.

The current databases are unable to adequately address the effect of silica fume and cenosphere as alternative cementitious materials used in the concrete mix designs 32, 36 and 49 (as shown in Figure 7 and 8). However, it is reasonable to assume that there is no environmental impact associated to silica fume as it is a by-product of the production of metallurgical grade silicon [71]. In addition, the embodied CO_2-e associated with cenosphere is similar to CO_2-e of fly ash and was therefore assumed to be the same as fly ash in the paper, as both materials are by-products from the production of power within coal fired power stations [62].

The resulting embodied CO_2-e when using different inventory databases are summarised in Figures 9 and 10. The embodied CO_2-e values across Alcorn, Crawford and eTool databases vary from 255 to 540 kg CO_2-e/m^3 for group 32-35 MPa and from 290 to 590 kg CO_2-e/m^3 for group 38-42 MPa. The differences could be explained by the variations in the method of analysis used in each database, the different system boundaries, source of data and quality of input in the calculation of the upstream process [72].

The embodied CO_2-e factor from ICE database varies for each different mix design with exception of mix design 32, 36, 39 which includes silica fume and cenosphere. This database considers different proportions of cement and cementitious material such a slag and fly ash in the concrete. In terms of the maximum proportion of the slag in mix designs 13 and 25, the ICE embodied CO_2-e coefficients are 62.8 and 70.3 kg CO_2-e/m^3. For specific mix designs, the ICE results match closely with those obtained from Crawford (mix 1, 3, 68, 79) and Alcorn (mix 43, 47,61). For mix designs 6 and 9 the ICE results are the same as the results from BPIC.

A comparison analysis between AusLCI, Alcorn and the current study demonstrates considerable variation in embodied CO_2-e of the concrete mix designs. The average differences are 16 % and 7% for grade 32 and 40 MPa, respectively. These differences in results are due to variations in the embodied CO_2-e coefficients for cement (general purpose), GGBFS, fly ash and type of aggregates (natural and manufactured) in concrete mix designs. For instance, AusLCI proposes the factor of 0.994 (tonne CO_2-e) for producing the average of 1 tonne GP cement in Australian, while this number 18% higher than the coefficients proposed in Crossin [71] and Flower [49] studies (used in this study). Similarly, AusLCI proposes a higher emission factor for manufacturing GGBFS and recycled aggregates and lower embodied CO_2-e for producing fly ash than this study (based on [49]). The embodied CO_2-e associated with the production of natural aggregates is not directly reported in a transparent way in AusLCI, while ARRB gives a value of 3.97 kg CO2-e per tonne of materials [61]. Also, Alcorn's database does not adequately address the embodied CO_2-e associated with alternative cementitious materials such as fly ash and GGBFS.

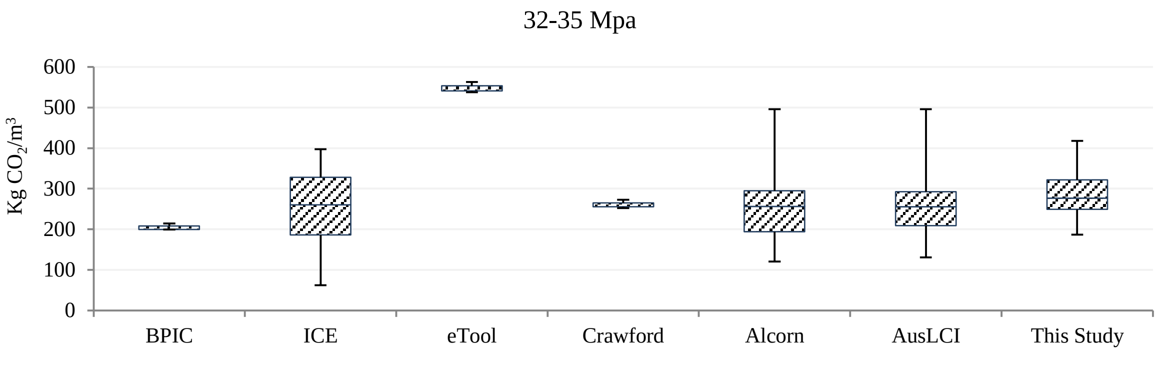

Figure 9 Variation in embodied CO_2-e for different databases (32-35 MPa)

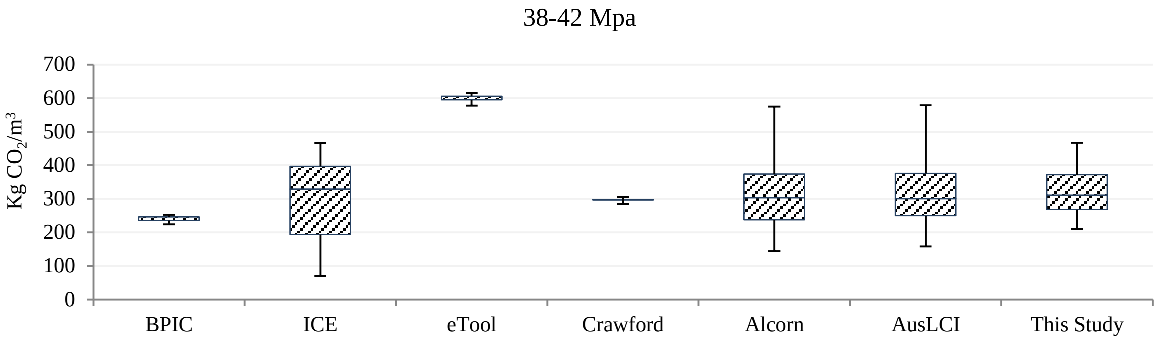

Figure 10 Variation in embodied CO_2-e for different databases (38-42 MPa)

In summary, it can be seen these variations in the embodied CO_2-e of different concrete mix designs could affect the overall lifecycle assessment of a building and building materials. As it can be seen from the results, one product might get attributed lower embodied CO_2-e than another product in one database while the same product in another database could get attributed the same or higher emissions. For example, the results based on AusLCI, Alcorn, ICE and those produced from the additional cases of our study show that mix designs 13, 18, 22, 26 represent the lowest amount of embodied CO_2-e among the 90 mix designs. These four mix designs (13, 18, 22 and 26) have used an alternative cementitious material by replacing 65% of cement binder with GGBFS. However, the results from eTool, BPIC and Crawford databases do not show these differences of embodied CO_2-e across the different concrete mixes. In addition, consideration needs to be given to the variation associated with production, manufacturing techniques, type of fuel used and the source of raw materials and transportation distance across different geographic location. This variation can even be quite significant between areas within the same country [2, 73]. The differences found between the databases point out the need for transparency with regard to their ability to analyse individual concrete components. Meanwhile, the summary of the results (Figures 9 and 10) quantify the variations which could promote better comparisons for research which employs these databases.

3-3 Thermal conductivity of concrete mix design

A comparative assessment was performed to estimate the thermal conductivity of each concrete mix designs. The thermal conductivities were obtained for all 90 mixes from ACI122R [15]. In addition, data for mixes 27 to 57 were reported in the relevant published articles [54, 55]obtained. The proposed ACI values were taken from Table 3.a of ACI122R-2014 and are based on practical thermal conductivity design values for normal weight (2240 to 2400 kg/m³), light and ultra-lightweight concrete (less than 1840 kg/m³). Figure 11 illustrates both theoretical and experimental thermal conductivity values for all 90 concrete mix designs. This paper used the data obtained from ACI122R method to ensure consistency comparisons across all mix designs. As expected, it can be seen that the thermal conductivity is influenced by the variation in the concrete mixture.

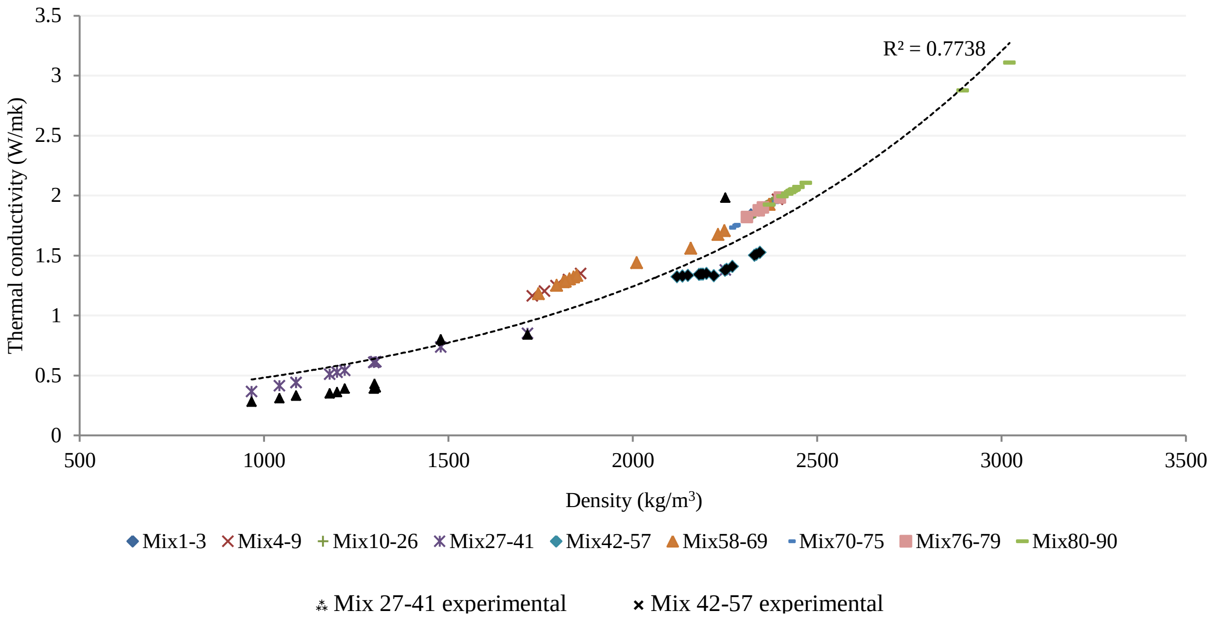

Figure 11 Thermal conductivity of concrete mix designs

The study shows that the type of cement and aggregate affected the density and thermal conductivity of the concrete. The replacement of normal aggregate with the lightweight aggregate reduces the density and thermal conductivity of the concrete. The data illustrate that by using lightweight aggregate to replace natural coarse aggregate, the concrete density can be changed from 2320 to 1727 kg/m^3. The thermal conductivity of concrete was decreased when lightweight aggregates introduced into the mix designs. For example, when comparing the results between mix 4 and mix 9 it can be seen that with the decreases of the proportion of aggregates in a mix design the thermal conductivity of the concrete decreased from 1.96 to 1.16 (W/mK).

Figure 12 represents the variation in thermal conductivity per m^3 of concrete across the two selected grades, i.e. mix design groups 32-35 MPa and 38-42 MPa. This variation in results is due to changes in the proportion of normal and lightweight aggregates in the concrete mixture. For example, mix designs 32 and 36 have the lowest thermal conductivity while having a lower density than all other mix designs in groups 32-35 MPa and 38-42 MPa, respectively.

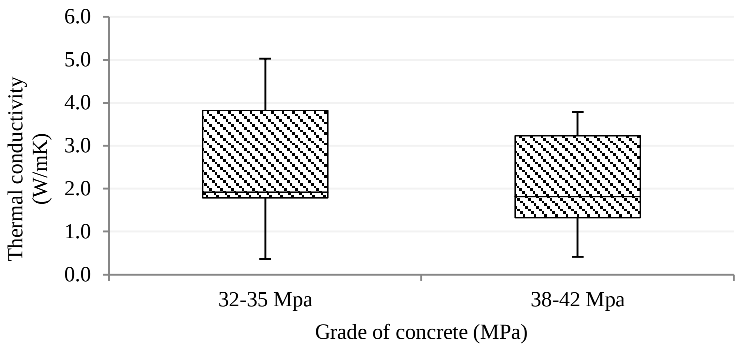

Figure 12 Variation in thermal conductivity between concrete mix designs

With a brief review of previously published values, it can be seen that the estimated thermal conductivity for grade 32-35 MPa and 38-42 MPa concrete mixes could vary from as high as 3.1 W/(m.K) to as low as 0.36 W/(m.K). For a grade of 32-35 MPa, the lowest and highest thermal conductivity is found for a mix design 32 and 82, respectively. For 38-42 MPa, the lowest thermal conductivity (0.31 W/(m.K)) can be achieved by through mix design 36.

The comparison of all embodied CO_2-e obtained from Table 3 and thermal conductivity of mix designs show different correlations between two variables. Figure 13 plots changes of the embodied CO_2-e results against thermal conductivity of concrete mix designs and also shown in Appendix 1.

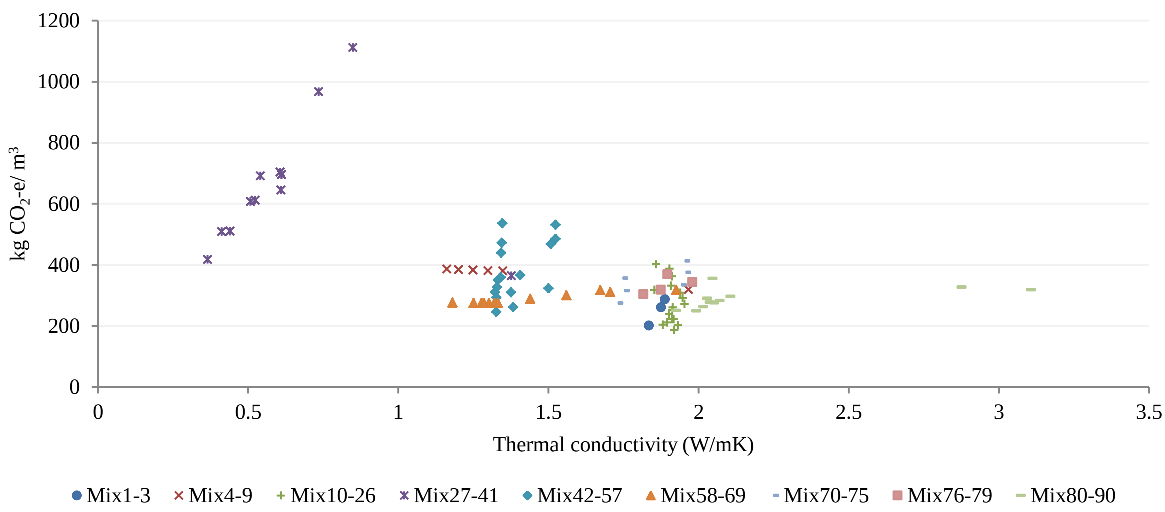

Figure 13 Embodied CO2-e versus thermal conductivity across all concrete mix designs

For mix designs 27-41, the results represent a positive gradient between changes of thermal conductivity and embodied CO_2-e. In the other words, the amount of embodied CO_2-e was increased by increasing the thermal conductivity of concrete. It was noted that the rate of changes embodied CO_2-e and thermal conductivity for mixes 27-41 are much higher than the other mixes. These changes are due to the presence of high proportion of Portland cement and low-density aggregates in the mixes 27-41. On the other hand, the results from several other mix designs demonstrate considerable scatter in thermal conductivity without changing embodied CO_2-e values and vice versa. This can be seen, for example, in mix designs 4 to 9, where the changes in thermal conductivities ranged up to 41% while there was just 17% change in embodied CO_2-e value.

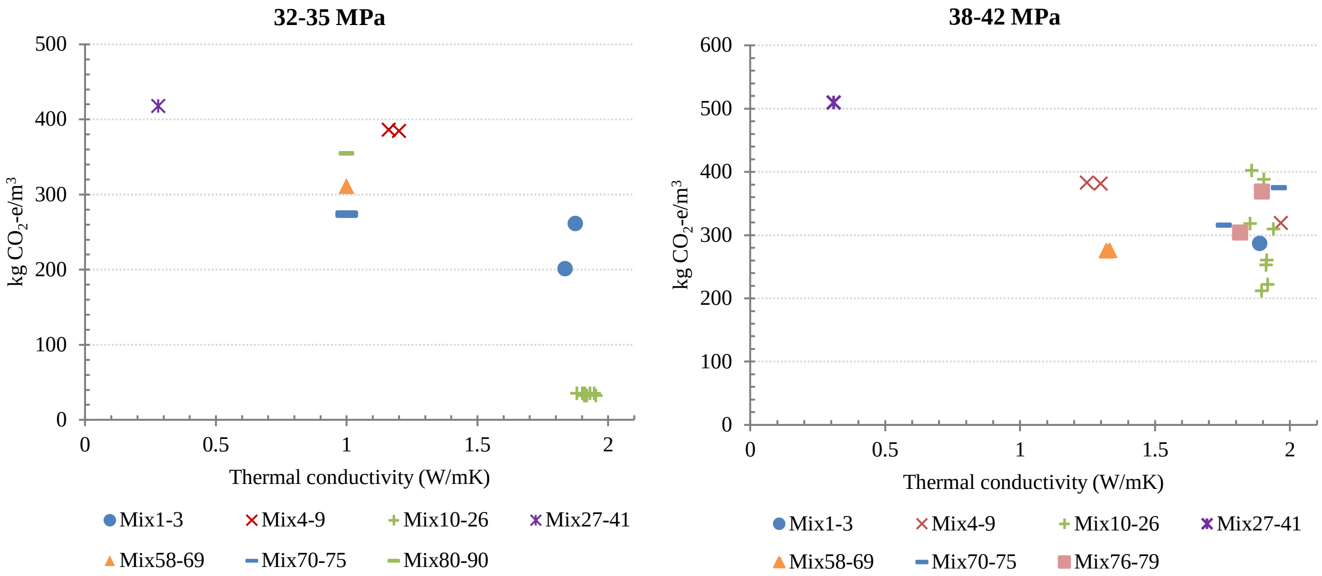

Figure 14 Embodied CO2-e against the thermal conductivity for Grade 32-35 MPa and 38-42 MPa

Figure 14 illustrates a comparison between the thermal conductivity and the embodied CO_2-e of the 32-35MPa and 38-42MPa concrete groups. It can be seen mixes 27-41 provide lowest thermal conductivity while having the highest embodied CO_2-e. Mix designs 10-26 are associated with the lowest amount of embodied CO_2-e while presenting the highest thermal conductivity in both groups. In group 38-42 MPa, the thermal conductivity values associated with mix design 10-26 do not vary significantly while the values of the embodied CO2-e can range from approximately 200 to 400 kg CO_2-e/m^3.

As previously discussed, the variations of the results are shown in Figures 11-14 are associated with the changes in quantity and type of aggregate and binder materials in the concrete mix design. Also, The lower thermal conductivity suppresses the energy charging/discharging rates [74]. This may have a positive potential effect on the overall energy performance of buildings in compare to the traditional concrete. Concrete with the low thermal conductivity results in higher thermal resistance than conventional concrete, which can slow down heat gain and energy losses for periods of time [75, 76]. However, the optimal range for thermal conductivity of a concrete mix has to be considered to reduce either escape of passive heating before being absorbed or re-released a stored heat before the colder night [14]. It is, therefore, essential to consider the environmental impacts of concrete mix designs during the structural design of buildings in a more holistic way and include estimated impacts on energy performance during the operational phase and end of life (life cycle) of a building. Future research will quantify the potential effects of conventional and novel concrete materials on thermal performance of buildings.

Conclusion

There are presently many efforts on compiling reliable methodologies for quantifying the environmental impacts of concrete production. Some of the available embodied emissions databases (eTool, Crawford, BPIC) propose an individual embodied CO_2-e coefficient for each grade of concrete without considering variations across different mix designs. The findings from this study are consistent with the common literature and confirm that significant reductions in embodied CO_2-e can be achieved by using supplementary cementitious materials such as fly ash, and GGBFS. Depending on the percentage of cement replacement, fly ash can typically contribute to reducing the embodied CO_2-e of concrete by 10 to 15% when compared with Portland cement. GGBFS was also found to be capable of reducing concrete embodied CO_2-e by 15.5% in comparison with common Portland cement.

The embodied CO_2-e analyses have shown variations across the different inventory databases. These recorded variations in embodied CO_2-e are due to the different methods of analysis used in the different databases, the source of data and quality of input data (related to upstream process) in calculation. This highlights the need for transparency within existing and future databases and imposes a requirement for extending their capabilities to be able to model concrete mix design based on individual components.

When using the ICE database, the results for the embodied CO_2-e were sensitive to the concrete mix design because the embodied CO_2-e coefficients in ICE varied in accordance with the different percentages of cement, fly ash and GGBFS. From the analysis, it was shown that the embodied CO_2-e of a mix design decreases by increasing the proportion of fly ash and GGBFS in the concrete binder. The slight limitation of the ICE database is that it does not take into account the effects of silica fume and cenosphere in concrete admixture mix, though these can be accounted for by including the cenosphere as additional fly ash and considering silica fume as a zero contribution.

The inventory databases from Crawford and eTool use the same embodied CO_2-es coefficients for each grade of concrete without accounting for the effects of each different concrete component. The calculated embodied CO_2-e from BPIC database which uses average industry values results in lower embodied CO_2-e than those calculated with Crawford and eTool databases.

However, the analysis based on the AusLCI, Alcorn's analysis and embodied CO_2-e coefficients (Table 3) that were compiled for the purposes of this study considered the detailed effects of the materials in the concrete mix design. A considerable variation in embodied CO_2-e of concrete mix designs was found. Meanwhile, there are some discrepancies between the results of this study and the AusLCI analysis. The discrepancies are due to differences in embodied CO_2-e factor for Portland cement, fly ash, GGBFS and type of aggregates (recycled, natural and manufactured).

This study also demonstrates that the thermal conductivity of concrete is strongly related to the properties of the concrete mixes and the proportions of its constituents. In general, the thermal conductivity of a mix design increases with increasing density. The replacement of normal aggregates with lightweight aggregates significantly decreases the thermal conductivity of concrete. The lower density concrete mixes by having low thermal conductivity could be beneficial in terms of energy saving during the operational phase of buildings. On the other hand, it was found that lower density concrete mix designs could have high embodied CO_2-e. Hence, it is crucial to understand and considered the thermal and environmental impacts associated with the concrete mix designs in an integrated way and at the design stage of building.

The results of this study can be used as guidance for considering reductions on the environmental impact and improving the thermal conductivity of concrete while maintaining the desired concrete strength during the early stages of building projects. Further studies will need to consider the potential impact of concrete mix design on specific heat and thermal mass and hence on the energy performance of a building over its operation phase and its entire life cycle.

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Appendix 1- Mix properties of different batches of concrete

Mix Numbers	References	strength (MPa)	Binder (kg/m^3)						Aggregates (kg/m^3)					Admixture (liter)						Water (g/m^3)		Density (kg/m^3)	Conductivity (W/mk)	kg CO_2-e/ m^3 product
			Portland cement	GGBFS	Fly ash	silica fume	Furnace bottom ash	cenosphere	Natural aggregates	Recycled aggregates	Manufactured Sand	Fine natural river sand	Lightweight aggregate	Water reducing admixture	Superplasticiser	shrinkage reduction	Viscosity modifying agent	Polyethylene fibres	Silane	Potable water	Reclaimed water			
1	[51]	32	175	120	80	...	...	...	546	455	270	532	...	1.3	...	...	...	...	...	...	141	2320.3	1.84	200.9
2		32	255	85	35	...	...	...	549	445	245	589	...	1.3	...	...	...	...	...	68	70	2342.3	1.88	260.8
3		40	260	80	125	...	...	...	1067	...	90	580	...	1.6	...	...	...	...	...	76	70	2349.6	1.89	286.3
4	[52]	39.4	325	...	...	...	...	...	828	...	1041	...	...	3.6	...	...	...	...	...	195	...	2392.6	1.97	319.0
5		46.8	450	...	...	...	...	...	...	...	755	...	477	1.5	...	...	...	...	...	175	...	1858.5	1.35	401.4
6		42.7	450	...	...	...	156	...	...	...	566	...	477	2	...	...	...	...	...	175	...	1826.0	1.30	403.0
7		40.9	450	...	...	...	312	...	...	...	377	...	477	1.4	...	...	...	...	...	175	...	1792.4	1.25	404.6
8		34.1	450	...	...	...	468	...	...	...	189	...	477	1.9	...	...	...	...	...	175	...	1760.9	1.20	406.2
9		31.6	450	...	...	...	624	...	...	...	...	...	477	1.8	...	...	...	...	...	175	...	1727.8	1.16	407.7
10	[53]	32	330	...	...	...	...	...	1093	...	778	...	...	...	...	...	...	...	...	160	...	2361.0	1.91	331.6
11		32	254	...	84.5	...	...	...	1090	...	787	...	...	...	...	...	...	...	...	170	...	2385.2	1.95	271.7
12		32	168	...	...	...	...	...	1089	...	774	...	...	...	...	...	...	...	...	164	...	2362.2	1.91	222.0
13		32	116	...	...	...	...	...	1095	...	780	...	...	...	...	...	...	...	...	159	...	2366.4	1.92	187.2
14		35	370	...	...	...	...	...	1035	...	801	...	...	...	...	...	...	...	...	157	...	2362.7	1.91	362.0
15		35	280	...	93	...	...	...	1054	...	797	...	...	...	...	...	...	...	...	158	...	2382.0	1.95	291.6
16		35	188	...	...	...	...	...	1039	...	784	...	...	...	...	...	...	...	...	158	...	2357.0	1.90	239.6
17		35	196	...	...	...	...	...	...	1053	743.4	...	...	...	...	...	...	...	...	157	...	2345.3	1.88	203.4
18		35	131	...	...	...	...	...	1061	...	780	...	...	...	...	...	...	...	...	158	...	2373.5	1.93	202.1
19		40	400	...	...	...	...	...	1080	...	710	...	...	...	...	...	...	...	...	168	...	2358.0	1.90	387.4
20		40	300	...	100	...	...	...	1095	...	719	...	...	...	...	...	...	...	...	164	...	2378.0	1.94	309.0
21		40	200	...	...	...	...	...	1082	...	715	...	...	...	...	...	...	...	...	166	...	2363.0	1.91	252.2
22		40	140	...	...	...	...	...	1075	...	712	...	...	...	...	...	...	...	...	167	...	2353.8	1.90	211.2
23		40	420	...	...	...	...	...	1030	...	715	...	...	...	...	...	...	...	...	168	...	2333.0	1.86	401.6
24		40	315	...	105	...	...	...	1020	...	718	...	...	...	...	...	...	...	...	172	...	2330.2	1.85	317.9
25		40	210	...	...	...	...	...	1040	...	740	...	...	...	...	...	...	...	...	164	...	2363.8	1.91	260.3
26		40	151	...	...	...	...	...	1048	...	720	...	...	...	...	...	...	...	...	168	...	2365.7	1.92	221.5
27	[54]	67.6	377	...	...	33	...	...	946	...	810	...	...	...	5.4	...	...	...	...	172	...	2343.4	1.98	364.9
28		69.4	836	...	...	73	...	348	...	...	...	...	...	...	4.9	10.5	...	...	...	302	...	1574.4	0.40	697.1
29		56.9	732	...	...	64	...	402	...	...	...	...	...	...	5.2	9.8	...	...	...	282	...	1495.0	0.36	613.1
30		55.9	731	...	...	64	...	268	...	...	...	...	...	...	5.9	8.9	0.2	...	...	287	...	1365.0	0.35	608.7
31		48.8	607	...	...	53	...	442	...	...	...	...	...	...	5.6	9.8	...	...	...	282	...	1399.4	0.33	511.3
32		33	499	...	...	43	...	317	...	...	...	...	...	...	6.6	9.1	0.2	...	...	290	...	1164.9	0.28	418.6
33		66.1	846	...	...	74	...	352	...	...	...	...	...	...	5.2	...	...	...	...	305	...	1582.2	0.39	705.6
34		69.4	836	...	...	73	...	348	...	...	...	...	...	...	4.9	10.5	...	...	...	302	...	1574.4	0.40	697.1
35		49.8	607	...	...	53	...	442	...	...	...	...	...	...	5.6	9.8	...	...	...	282	...	1399.4	0.33	511.3
36		40.9	606	...	...	53	...	442	...	...	...	...	...	...	6.7	9.7	0.18	...	...	282	...	1399.6	0.31	510.5
37		66.1	846	...	...	74	...	352	...	...	...	...	...	...	5.2	...	...	...	...	305	...	1582.2	0.39	705.6
38		66.5	775	...	...	67	...	350	...	...	...	...	...	...	3.6	...	...	5.3	4.2	304	...	1509.1	0.43	646.5
39		54.4	832	...	...	72	...	346	...	...	...	...	...	...	4.3	...	...	5.7	...	301	...	1561.0	0.39	693.3
40		63.1	1355	...	...	118	...	...	...	...	...	...	...	...	1.3	14.9	...	...	...	499	...	1988.2	0.84	1114.4
41		51.3	1179	...	...	103	...	...	...	...	...	...	...	...	...	16.9	0.91	...	...	561	...	1860.8	0.80	969.9
42	[55]	45	345	...	...	...	...	...	1826	...	...	...	...	...	...	...	...	...	...	195	...	2366.0	0.92	366.7
43		42	190	155	...	...	...	...	1826	...	...	...	...	...	...	...	...	...	...	195	...	2366.0	0.88	261.8
44		41	295	...	60	...	...	...	1802	...	...	...	...	...	...	...	...	...	...	185	...	2342.0	0.82	326.2
45		43	275	...	...	70	...	...	1826	...	...	...	...	...	...	...	...	...	...	195	...	2366.0	0.84	311.2
46		39	345	...	...	...	...	...	1447	...	...	...	...	...	...	...	...	...	...	204	...	2361.0	0.72	350.8
47		42	190	155	...	...	...	...	1447	...	...	...	...	...	...	...	...	...	...	204	...	2361.0	0.67	245.8
48		41	295	...	60	...	...	...	1438	...	...	...	...	...	...	...	...	...	...	189	...	2342.0	0.61	311.0
49		38	275	...	...	70	...	...	1447	...	...	...	...	...	...	...	...	...	...	204	...	2361.0	0.65	295.3
50		55	557	...	...	...	...	...	1610	...	...	...	...	...	...	...	...	...	...	195	...	2362.0	0.99	530.6
51		51	251	306	...	...	...	...	1610	...	...	...	...	...	...	...	...	...	...	195	...	2362.0	0.93	323.5
52		53	478	...	120	...	...	...	1583	...	...	...	...	...	...	...	...	...	...	180	...	2361.0	0.89	467.9
53		54	501	...	...	111	...	...	1610	...	...	...	...	...	...	...	...	...	...	195	...	2417.0	0.90	487.7
54		54	583	...	...	...	...	...	1234	...	...	...	...	...	...	...	...	...	...	204	...	2358.0	0.77	536.0
55		49	321	262	...	...	...	...	1234	337	...	...	...	...	...	...	...	...	...	204	...	2358.0	0.73	358.7
56		48	502	...	126	...	...	...	1212	331	...	...	...	...	...	...	...	...	...	190	...	2361.0	0.70	472.0
57		52	466	...	...	117	...	...	1234	337	...	...	...	...	...	...	...	...	...	204	...	2358.0	0.75	443.3

58		43.9	288	...	32	...	...	...	1756	...	...	...	...	...	...	...	...	...	...	175	...	2251.0	1.93	317.6
59		NA	288	...	32	...	...	6	1730	...	...	...	...	...	...	...	...	...	...	175	...	2231.0	1.67	316.6
60		35.3	288	...	32	...	...	12	1602	...	...	...	...	...	...	...	...	...	...	175	...	2109.0	1.71	310.9
61		32.1	288	...	32	...	...	24	1364	...	...	...	...	...	...	...	...	...	...	175	...	1883.0	1.56	300.3
62		24.6	288	...	32	...	...	37	1097	...	...	...	...	...	...	...	...	...	...	175	...	1629.0	1.44	288.4
63	[56]	37.5	288	...	32	...	...	...	826	...	...	...	552	...	...	...	...	...	...	175	...	1873.0	1.32	300.3
64		36.2	288	...	32	...	...	12	826	...	...	...	409	...	...	...	...	...	...	175	...	1742.0	1.28	294.0
65		28.1	288	...	32	...	...	23	826	...	...	...	276	...	...	...	...	...	...	175	...	1620.0	1.25	288.2
66		23	288	...	32	...	...	35	826	...	...	...	127	...	...	...	...	...	...	175	...	1483.0	1.18	281.7
67		37.7	288	...	32	...	...	...	834	...	...	...	583	...	...	...	...	...	...	175	...	1912.0	1.33	302.1
68		33	288	...	32	...	...	23	826	...	...	...	289	...	...	...	...	...	...	175	...	1633.0	1.30	288.8
69		36	288	...	32	...	...	...	834	...	...	...	510	...	...	...	...	...	...	175	...	1839.0	1.29	298.7
70		36.6	300	...	...	...	...	...	1902	...	...	...	...	...	...	...	...	...	...	179	...	2381.0	1.95	333.3
71		41.8	353	...	...	...	...	...	1854	...	...	...	...	...	...	...	...	...	...	182	...	2389.0	1.96	374.6
72	[77]	48.6	402	...	...	...	...	...	1798	...	...	...	...	...	...	...	...	...	...	188	...	2388.0	1.96	412.2
73		33.6	300	...	...	...	...	...	611	...	...	...	...	...	...	...	...	...	...	179	40	1130.0	1.73	274.0
74		41.1	351	...	...	...	...	...	596	...	...	...	...	...	...	...	...	...	...	183	39	1169.0	1.76	315.2
75		48.1	402	...	...	...	...	...	579	...	...	...	...	...	...	...	...	...	...	189	29	1199.0	1.75	356.2
76		43.7	354	...	...	...	...	...	1164	...	...	...	...	...	...	...	...	...	...	185	...	1703.0	1.98	343.7
77	[58]	41.5	384	...	...	...	...	...	1165	...	...	...	...	...	...	...	...	...	...	201	...	1750.0	1.90	368.4
78		44.2	354	...	...	...	...	...	555	555	...	...	...	...	...	...	...	...	...	185	20	1669.0	1.87	318.0
79		42.5	365	...	...	...	...	...	...	1071	...	...	...	...	...	...	...	...	...	180	38	1654.0	1.82	303.6
80		32	324	...	...	...	...	...	1929	...	...	...	...	...	...	...	...	...	...	184	...	2437.0	2.05	354.2
81		32	273	...	510	...	...	...	1931	...	...	...	...	...	...	...	...	...	...	181	...	2895.0	2.88	326.3
82		32	258	...	660	...	...	...	1921	...	...	...	...	...	...	...	...	...	...	183	...	3022.1	3.11	317.6
83		32	243	...	81	...	...	...	1923	...	...	...	...	...	...	...	...	...	...	180	...	2427.0	2.03	289.7
84		32	227	...	96	...	...	...	1924	...	...	...	...	...	...	...	...	...	...	185	...	2432.0	2.04	277.0
85	[59]	32	192	...	128	...	...	...	1910	...	...	...	...	...	...	...	...	...	...	177	...	2407.0	1.99	248.6
86		32	240	80	...	...	...	...	1910	...	...	...	...	...	...	...	...	...	...	240	...	2470.0	2.11	295.9
87		32	220	100	...	...	...	...	1910	...	...	...	...	...	...	...	...	...	...	220	...	2450.0	2.07	282.4
88		32	210	110	...	...	...	...	1910	...	...	...	...	...	...	...	...	...	...	210	...	2440.0	2.05	275.6
89		32	190	130	...	...	...	...	1910	...	...	...	...	...	...	...	...	...	...	190	...	2420.0	2.02	262.1
90		32	180	100	...	...	...	...	1910	...	...	...	...	...	...	...	...	...	...	180	...	2370.0	1.93	249.6