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Environmental evaluation of pavement system incorporating recycled concrete aggregate

Issara Sereewatthanawut [a], Lapyote Prasittisopin [a,b]*

[a] *Faculty of Engineering and Technology, Pathumthani University, Pathumthani 12000 Thailand*
[b] *Siam Cement Group - Cement, Bangkok 10800 Thailand*

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Abstract

Environmental benefits of using recycled concrete aggregate (RCA) regarding a concrete pavement structure should be evaluated because standard specification for RCA as a raw material in RMC is not currently in place in many locations. This work aims to address environmental benefits of using RCA of concrete pavement structures using a Life Cycle Assessment (LCA) analysis. Two concrete mix designs and two mix ingredients containing RCA and natural aggregate (NA) are determined at 10% and 20% replacement levels. Results indicate that using RCA in pavements can result in decreases of environmental impacts regarding energy consumption, water consumption and CO_2, PM10, and RCA waste generation, but result in increases of NOx and human toxicity potential (cancer and non-cancer) generation. Using the RCA in concrete pavement can ultimately reduce the negative environmental impacts, especially for energy consumption. Nonetheless, selecting the suitable concrete mix design should be carefully determined for each application since the negative environmental impacts can be significantly decreased.

Keywords: Environmental evaluation; Pavement; Recycled concrete aggregate; Life cycle assessment

1. Introduction

A construction and building activity nowadays consumes a tremendous amount of virgin material generated from natural resources and this activity seems to also generate a large amount of waste. Serious concerns growing on environmental impacts including an increase of footprint of landfills, a difficulty of handling the waste, and a quick depletion of valuable natural resource, are driving forces stimulating a development of recycling processes to occur in these industries. The development of the recycling processes of the waste and the solid waste stream are in the big steps towards sustainable construction and building applications such as using a reclaimed asphalt, recycled ceramic, recycled tire, recycled glass, recycled plastic, geopolymer, supplementary cementing material, and recycled concrete aggregate (RCA) [1-11].

A construction and demolition (C&D) waste generated from demolishing an existing construction and building projects accounts for a large fraction of solid waste. According to Advancing Sustainable Material Management Fact Sheet [12], approximately 534 million tons of C&D waste was generated in the U.S. in 2014. This large volume of C&D waste was about two times higher than the solid waste generated from municipal activities. It is also reported that the demolition activity generated waste associated with more than 90% of the total C&D waste generation, while the construction activity generated waste associated with less than 10% of the total C&D waste generation. The demolition activity is a main contribution in civil engineering industry these days and mainly consumes great volume of energy. The World Business Council for Sustainable Development (WBCSD) [13] reported that over 900 million tons of the C&D waste were generated annually in Europe, the U.S., and Japan. Much of C&D waste is generated each year and this brings about the idea of recycling the waste. Not only is the performance and quality of the C&D waste critical for recycling processes, but also the waste classification process during demolition can allow it to reuse back in roads, drainage, and other construction projects such as structural ready-mixed concrete (RMC) or prefabrication concrete production. However, this recycling potential is still under-exploited in some regions where the recycling rate is still low [14]. Not many countries seem to successfully utilize the C&D waste back in the RMC and prefabrication construction while the rest in somewhat shows little-to-none economic benefit [15].

The recycling process of the C&D waste is a vital challenge fostering many research and development programs towards sustainability in civil engineering and building industries [16-24].

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* Corresponding author
E-mail address: lapyote@gmail.com (L. Prasittisopin).
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In their works, mainly RCA was determined. The RCA, as shown in Fig. 1, is believed to be a comparative high quality material among other debris from C&D waste such as steel reinforcement, paper, wood, plastic, and gypsum. This is because when the above debris presents in the C&D waste, they are considered as contamination. With the large percentage of contamination, the concrete performance is deteriorated. The RCA with no contamination has high potential to be utilized as coarse aggregate in concrete mixtures without significantly deteriorating its performance – when using at lower replacement levels. The research and development programs regarding the replacement of natural aggregate (NA) with RCA have been performed focusing on investigating concrete performance both fresh and hardened characteristics. These programs also emphasizes on the coarse RCA part, not for the fine RCA part. The fine RCA is not suggested to use in concrete mixtures because when using it, the concrete mixtures likely have a serious negative impact on concrete performance [25-27]. The replacement level of coarse RCA can be typically used approximately up to 20 to 30%. Prasittisopin et al. [19-21] developed a coating process of RCA and this method allows coarse RCA to replace the NA up to 100% without lowering its performance. This is because the coating process leads to the improvement of the interfacial transition zone (ITZ) between the RCA's surface and cement paste, resulting in better quality of RCA mixture. The authors also developed the pilot-scale tube mill in Thailand to improve RCA quality by grinding or removing the mortar part detaching from the aggregate part [24]. The detachment of mortar resulted in reduced water absorption and increased specific gravity. The performance characteristics of processed-RCA concrete were enhanced noticeably. The RCA quality improvement process can broaden its use in civil engineering applications. Although there is still a doubt on how much additional energy is consumed in the quality improvement processes. These quality improvement processes are still required for future investigation of quantification of energy consumption. Considering the fact that the coarse aggregate occupies approximately 30 and 40% of the total concrete volume. Only partial RCA replacement can play a critical role to environmental impact of aggregate consumption and civil engineering industry worldwide.

Recently, interests for the use of environmentally friendly concrete in the pavement design, material, construction, and maintenance have increased. The RCA is one of proper candidates used as a sustainable rigid pavement material. Although general use of RCA in many countries is using as subbase layer, embankment construction, and earth construction works, attempts to add RCA into wearing coarse layer can offer more economical value [28-29].

Fig. 1. Coarse RCA.

Although the substitution of RCA in rigid pavement structure offers environmental benefits compared to the use of 100% NA, there is still a doubt on how much is the better off on environmental performance when using such recycled material. This uncertainty on its environmental benefits is one of the main barriers making the use of RCA in concrete unconvincingly [30-31]. To clarify these issues, a quantification evaluation of environmental performance of using RCA and a selection of concrete mix design in the rigid pavement are necessary to address. This work presents the results calculated from a life cycle assessment (LCA) method of a typical rigid pavement structure. The LCA method offers an opportunity to quantify the eco-efficiency of such pavement systems with different RCA replacement levels and different concrete mix designs, serving the needs of society and the economy, while diminishing negative environmental treats such as global warming and energy consumption [32,33]. Regarding RCA, the LCA measuring the environmental performance of concrete has been conducted by several researchers [34-37]. Many LCA tools can be used to estimate the environmental benefits of using RCA.

Determining the concrete manufacturing activity in many developing countries, all RCA for making concrete are mandatory to use the NA as concrete aggregate since the standard specification of RMC [38] offers the use of NA only, leaving behind a large quantity of RCA going elsewhere (mainly in the aforementioned applications). It is reported that the return concrete has been used in precast concrete product [39] and non-structural pavement block [15]. Still, much effort is required to promote the use of RCA in concrete, rather than dumping in the landfill. To encourage recognition of using the RCA in more valuable applications such as aggregates for the RMC and the wearing course layer, addressing the LCA results of RCA substitution in the applications is critical. This paper aims to present the results from the LCA of the rigid pavement design incorporating RCA using local material data. The paper offers the evaluation of environmental impacts of using RCA in either the subbase or the concrete wearing course, compared to the NA. The LCA of the concrete mix design selection is also determined here. Results from this study are anticipated to increase the perception of users in construction and civil engineering industries in many developing countries for moving forward using much of RCA as concrete aggregate in the pavement structure.

This paper presents results from the LCA calculated by using Pavement LCA Tool for Environmental and Economic Effects (PaLATE) software version 2.0 [40]. The software was designed by the Consortium on Green Design and Manufacturing from the University of California-Berkeley. It should be noted there that the PaLATE software is selected to evaluate the environmental impact of the pavement structure in this study because the software is open source and has been used to evaluate the environmental impacts by many researchers. [41-48] Nahlik et al. [41] evaluated environmental performance of freight movement of material activity in California by the PaLATE and concluded that the CO_2 emission (as equivalent to global warming potential) could be reduced by using low-energy fuel. Selecting energy type for pavement construction can offer better environment performance. Lee et al. [43] reported the use of fly ash and foundry sand in base and subbase layer of the pavement in Wisconsin and exhibited approximately 20% and 16% reduction in global warming potential and energy consumption, respectively. Although fly ash and foundry sand were applied only for the base and subbase layer in their research, significant reduction on environmental impacts has been already achieved. Carpenter et al. [44] evaluated the use of bottom ash for replacing natural crushed rock and reported the very low transport of contamination of Cd, Cr, Se, and Ag from the bottom ash to groundwater. Their results encourage the replacement of bottom ash instead of crushed rock in pavement structure. However, using the bottom ash in pavement in many cases normally results in the reduction of its mechanical performance. The utilization of recycle materials can be successfully implemented into the structure only when its performance characteristics are in the same quality. Liu et al. [48] determined the LCA of real existing highway structures in China and they reported that selecting the material used in concrete pavement could contribute to the largest portion associated with the greenhouse gas emission. They also reported that the greenhouse gas emission of the high-grade pavement was 13% greater than the low-grade pavement. Research evaluating the use of RCA instead of NA in both low- and high-grade wearing coarse layer of pavement structure is needed.

To assess the overall environmental impact of the rigid pavement structure, all the life-cycle phase boundaries of a concrete pavement structure is required to investigate. These phase boundaries include (1) the production of materials and concrete phase, (2) construction phase, (3) use/operation phase, (4) maintenance phase, and (5) end-of-life phase. In this work, only the production of material of concrete and construction phases are evaluated. The flowchart of the PaLATE software process is as shown in Fig. 2. Neither are the use/operation, maintenance, nor end-of-life phases in evaluation in this work. This is due to the fact that many input data such as equipment used and maintenance methods are varied for each construction site, and could result in a less accurate results. It is also noted that in terms of performance characteristics and cost of material during construction, the effect of concrete properties during early ages were reportedly outweigh the properties during later ages [49,50].

2. Materials and methods

The LCA method is an evaluation framework for the environmental performance of processes and products during their life cycle. According to ISO 14040 [51] and ISO 14044 [52] standards, LCA comprises of four steps: defining goal and scope, creating the life cycle inventory (LCI), assessing the environmental impact, and analyzing the results.

The input data in PaLATE software of each construction phase including design, initial construction, maintenance, equipment, and cost were evaluated. The authors selected the PaLATE software to perform LCA in this study because the input data can be used local material data with more precise outcome. It should be noted that other LCA calculation program can also be used; however, the authors selected PaLATE because it is able to examine the pavement system suitably. Short supply distance was retained and the assumption has been made that transportation distance from recycling plants corresponding to pavement application. Because the transport of material components in Thailand is mostly by a diesel-engine truck, the data input here is used the truck as a vehicle for analysis. There are only a few stationary RCA plants in Thailand and mainly are located in the suburban area with the approximated distance around 100 to 150 km far from the demolition site. The RCA plants are located closed to the RMC batching plants (roughly within 0 to 3 km) so the distance transporting the RCA material to the RMC plants can be negligible. The NA, on the other hand, is typically crushed limestone and it is produced in a rock-crushing plant closed to the limestone source. The crushing plant is located far from the RMC batching plants with approximately 100 to 150 km and the RMC truck is dispatched to the construction site in the local area within 100 km. This is a normal case of producing the concrete aggregate and transporting the RMC.

Four types of pavement structures and two types of concrete mix design assessed are shown in Table 1. The mix designs are routinely used in the RMC plants and are conformed BS EN 206 [53]. It should be noted that the maximum replacement level of low-quality RCA equals 20% according to RILEM standard (Type III) [54]. The RCA replacement level up to 20% tends to be accepted for no reduction of concrete performance characteristics [55]. As a result, the maintenance and end-of-life phases of the pavement structures in this work calculated by the PaLATE are assumed to be the same. Nonetheless, a higher replacement level of RCA results in reduced concrete performance characteristics and this is not the case in this work. The experimental design herein is determined only at 0%, 10%, and 20% RCA replacement levels.

Table 1
Experimental design of pavement structures.

No.	Code	Wearing course	Subbase	Mix design
1	NA/NA-L	100% NA	100% NA	Low-grade
2	NA/RCA-L	100% NA	100% RCA	Low-grade
3	10% RCA/RCA-L	10% RCA	100% RCA	Low-grade
4	20% RCA/RCA-L	20% RCA	100% RCA	Low-grade
5	NA/NA-H	100% NA	100% NA	High-grade
6	NA/RCA-H	100% NA	100% RCA	High-grade
7	10% RCA/RCA-H	10% RCA	100% RCA	High-grade
8	20% RCA/RCA-H	20% RCA	100% RCA	High-grade

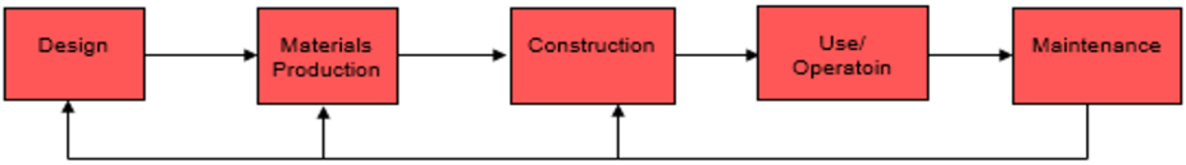

Fig. 2. Flowchart of PaLATE software process (adapted from [30]).

The designed structure of the pavement layers comprises of one wearing course and one subbase. The details of layer specifications are shown in Table 2. The period of analysis was designed at 40 years. As aforementioned, only the material production and construction phases of the LCA method were evaluated; neither was the maintenance, transportation, nor operation input analyzed. Typically, low- (28 MPa) and high-grade (42 MPa) concrete mix designs for constructing the concrete pavement structures in Thailand are selected as the wearing course layer. The low-grade pavement is mainly used for a local road and generally serviced for a four-wheel vehicles; whereas, the high-grade pavement is used for a factory pavement and highway designated to service for a small vehicle and truck with hauls. Their mix proportions and material costs of the 28-MPa and 42-MPa concretes are shown in Table 3. It is noted that the material cost of the 28-MPa and 42-MPa concretes are 6% difference. Ordinary portland cement (Type I) mixture was used. Their slumps were controlled at 5 to 10 cm. It should be noted here that the concrete mixtures containing pulverized fly ash are also normally casted for the pavement structure, this scope will be investigated in the future.

After inputting all data, the analysis presents 12 results of environmental impacts evaluated by the PaLATE software including energy consumption, water consumption, CO$_2$, NO$_x$, PM10 (particle matters less than 10 microns in diameter), SO$_2$, CO, Hg, Pb, Resource Conservation and Recovery Act (RCRA) hazardous waste generation, human toxicity potential (cancer), and human toxicity potential (non-cancer). All data were normalized by the maximum value of each analysis.

Table 2
Details of layer specification.

Layer	Width [m]	Length [m]	Depth [m]	Volume [m^3]
Wearing Course	3.05	1000	0.1	304
Subbase	3.05	1000	0.15	456

Table 3
28-MPa and 42-MPa concrete mix design and material cost.

Mix design of concrete per cu. m.			
Component	28 MPa	42 MPa	Unit
Cement[1]	284	350	kg
Water	195	195	kg
Fine aggregate	810	780	kg
Coarse aggregate	1150	1120	kg
Type D additive	1.14	1.40	L
Material cost[2]	63	67	USD

[1] The maximum aggregate size is 25 mm.

[2] The material cost based on the local material obtained at the manufacture's site.

3. Results

Results of 12 environmental impact study of eight different concrete mixtures including four pavement structures of two concrete grades are present in this section. Table 4 shows calculated values of environmental performance of reference mix design. It should be noted that the estimated values were calculated using assumptions as mentioned earlier.

3.1. Energy consumption

Determining the energy consumption during constructing the concrete structure pavement is very critical. Results of normalized energy consumption values of the NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems for low- and high-grade concrete mixtures are shown in Fig. 3. Results of the low-grade mixture indicate that the energy consumption of the NA/NA system is 1.9%, 2.6%, and 3.4% higher than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems, respectively. Regarding the high-grade mixture, the NA/NA system consumes energy 1.9%, 2.6%, and 3.3% higher than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems, respectively. Comparing results between the low-grade with the high-grade mixture, the energy consumption of the low-grade mixture is in the range of 14% to 15% lower than the high-grade mixture. Selecting suitable mix design for each application significantly reduces the energy consumption. Changing the concrete mix design can lead to the reduction of energy consumption greater than replacing RCA in concrete structure.

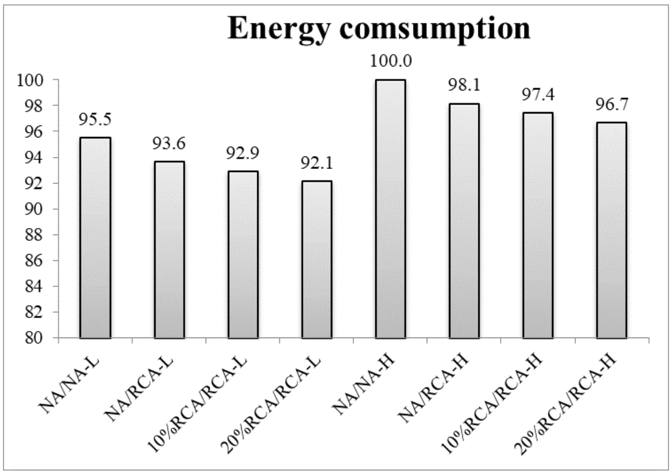

Fig. 3. Normalized energy consumption of different pavement systems and different mix designs.

Table 4
Calculated values of environmental performance of reference mix design.

Energy [MJ]	Water Consumption [kg]	CO$_2$ [Mg]	NO$_x$ [kg]	PM$_{10}$ [kg]	SO$_2$ [kg]	CO [kg]	Hg [g]	Pb [g]	RCRA Hazardous Waste [kg]	Human Toxicity Potential (Cancer)	Human Toxicity Potential (Non-cancer)
5.9E9	1906	433	6945	2379	3257	2945	9	519	1.2E5	2.2E5	1.1E10

3.2. *Water consumption*

The normalized values of the water consumption of the NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems for low- and high-grade concrete mixtures are shown in Fig. 4. Results indicate that the water consumption of the NA/NA system for the low-grade mixture is 0.97%, 1.37%, and 1.78% higher than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems, respectively. For the high-grade mixture, the water consumption of the NA/NA mixture is 0.97%, 1.36%, and 1.75% higher than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems, respectively. This indicates that when using the RCA in either subbase or wearing course layer, the water consumption is reduced. When comparing the water consumption of the low-grade with the high-grade mixture, the results exhibited that the low-grade mixture consumed less amount of water than the high-grade mixture by approximately 5% to 7%. Results here indicate that the emphasis of concrete mixture selection suitably for each application, should be implemented for reducing the water consumption.

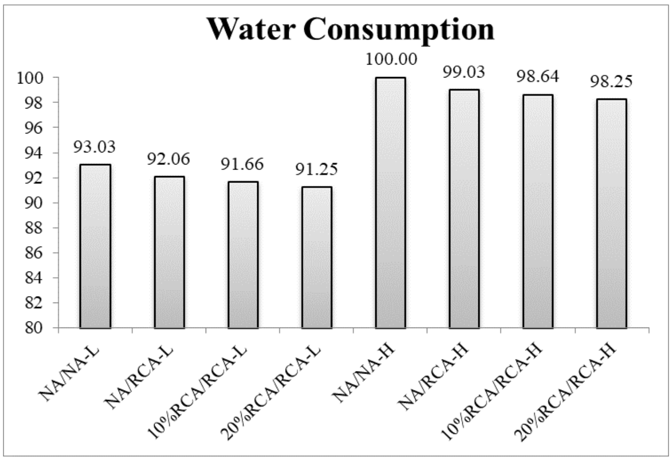

Fig. 4. Normalized water consumption of different pavement systems and different mix designs.

3.3. *CO_2*

The CO_2 gas emission from the cement and concrete industry influences our society tremendously. It is reported the cement and concrete industry contributed about 7% of total CO_2 emission worldwide [56-57]. A small reduction of CO_2 gas emission by using RCA instead of NA results in a large contribution of total CO_2 gas emission on earth. Fig. 5 shows the normalized values of the CO_2 gas emission for different pavement systems and different concrete mixtures. Results of the low-grade concrete mixture indicate that the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems have 2.3%, 2.3%, and 2.3% lower in CO_2 gas emission than the NA/NA system, respectively. The results of the high-grade concrete mixture exhibited similar results with the low-grade concrete mixture. The NA/NA system for the high-grade mixture releases CO_2 gas about 1.8% less than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems. For both low-grade and high-grade concrete mixtures, using the RCA in the subbase layer reduces the CO_2 gas emission; however, replacing the RCA in the wearing course layer does not mitigate the CO_2 gas emission. One benefit of using RCA as raw material for the subbase layer in pavement structure is lowering the CO_2 gas emission. Comparing the results of the low-grade mixture with the high-grade mixture, the CO_2 gas emission of the low-grade mixture is approximately 4% to 5% lower than the high-grade mixture. The selection of the mix design can result in a significantly reduction of CO_2 gas emission.

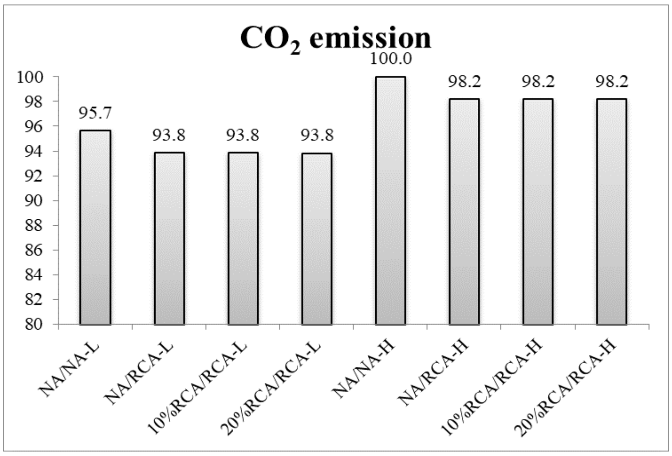

Fig. 5. Normalized CO_2 gas emission of different pavement systems and different mix designs.

3.4. *NO_x*

A concern of NO_x ($NO + NO_2$) emission came into amount since NO_x emission was reportedly a main reason of the ozone depletion [58]. The ozone depletion leads to global warming phenomenon and human health damage. Results from the normalized values of the LCA of the pavement structures of the low-grade and high-grade concrete mixtures containing different replacement levels of RCA are shown in Fig. 6. Results of the NO_x emission of the low-grade mixtures indicate that the NA/NA structure is 0.38%, 0.66%, and 0.94% lower than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems, respectively. Regarding the high-grade mixtures, the NO_x emission of the NA/NA system is 0.39%, 0.66%, and 0.93% lower than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems, respectively. The results comparing between low-grade and high grade mixtures exhibited that the NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems of the low-grade mixtures were 3.25%, 3.26%, 3.25%, and 3.24% lower than the NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems of the high-grade mixtures, respectively. Results of the NO_x emission in this section indicate that using the RCA substituted with NA in either subbase or wearing course layer results in the reduction of NO_x emission less than 1%, but selecting the appropriate concrete mix design can greater reduce the NO_x emission.

3.5. *PM10*

PM10 from construction industry is a dust matter that affects the lung and heart of human and possibly leading to different cardiopulmonary diseases and lung cancer [59]. During construction, the PM10 can release to the surrounding neighbourhood and also site workers. Fig. 7 shows the results of the normalized values of PM10 generation from different pavement systems (NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA) and different mix designs (low-grade and high-grade).

The PM10 results of the low-grade mixtures indicate that the NA/NA system releases PM10 greater than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems by 6.06%, 8.61%, and 11.16%, respectively. The results of the high-grade mixtures indicate that the NA/NA system releases PM10 more than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems by 6.06%, 8.54%, and 11.03%, respectively. When using RCA in concrete mixtures in subbase or wearing course layer, this results in a significant reduction of PM10 generation. Comparing the results of low-grade with the high-grade mixtures, the PM10 generation of the NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA of the low-grade mixtures are 0.98%, 0.98%, 1.05%, and 1.11% lower than the NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA of the high-grade mixtures, respectively. The PM10 results here indicate that RCA substitution in concrete can lead to the reduction of the PM10 generation greater than selecting the concrete mix design.

3.6. SO_2

The SO_2 gas emission and its acid derivations are known to cause considerable damage to materials. The SO_2 gas emission can be generated directly from cement industry including raw mill process, preheating process, calcining process, as well as burning process [60-61]. These SO_2 pollutants lead to an accelerated corrosion of ferrous and non-ferrous metals, consequently leading to reduced durability and service life of the structure [62]. In addition, Valavanidis et al. [59] reported that there was a relationship between increased concentrations of SO_2 and daily mortality, especially in urban areas. Results shown in Fig. 8 indicate the normalized value of SO_2 gas emission of different pavement structures. The results of the low-grade mixtures indicate that the NA/NA system has 0.19%, 0.26%, and 0.33% higher normalized value of SO_2 gas emission than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems, respectively. Regarding the high-grade mixtures, the normalized value of SO_2 gas emission of the NA/NA system exhibited 0.19%, 0.26%, and 0.33% higher than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems, respectively. Results comparing the low-grade with the high-grade mixtures indicate that the NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems of the low-grade mixtures are 7.02%, 7.02%, 7.02% and 7.02% lower than the NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems of the high-grade mixtures, respectively. The LCA results of the SO_2 gas emission showed that the mix design selection was more critical for implementation than use of RCA in pavement structure.

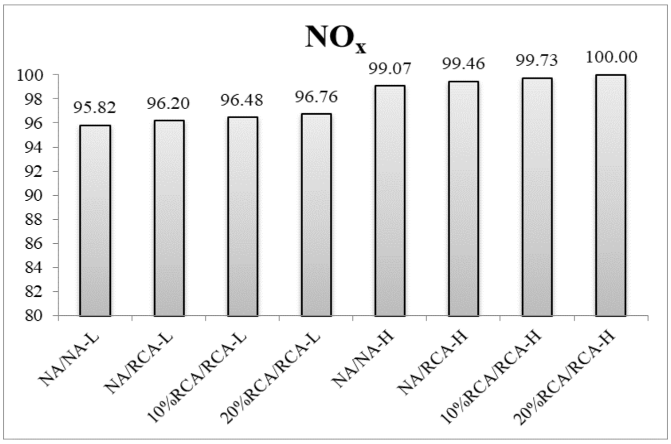

Fig. 6. Normalized NO_x gas emission of different pavement systems and different mix designs.

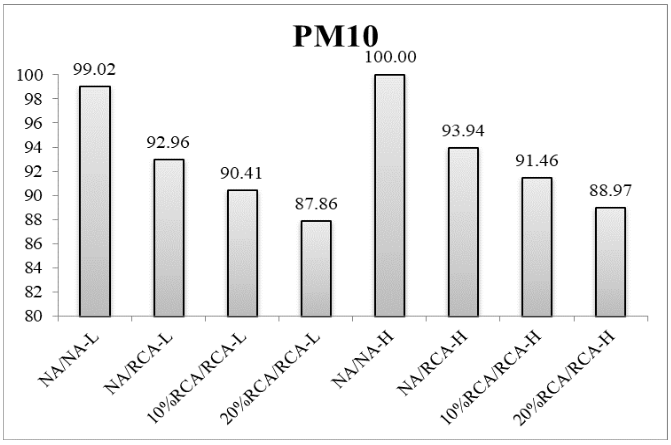

Fig. 7. Normalized PM10 generation of different pavement systems and different mix designs.

3.7. CO

CO gas emission affects human health by impairing the ability of the blood to bring O_2 to body tissues. Fig. 9 indicates the normalize values of the CO gas emission of the pavement structures with different RCA replacement levels and different concrete mix designs. For the low-grade mixtures, the NA/NA system releases CO gas by 0.07%, 0.07%, and 0.08% higher than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems, respectively. For the high-grade mixture, the results indicate that the CO gas emission of the NA/NA system is 0.07%, 0.07%, and 0.08% higher than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems, respectively. The use of RCA instead of NA in pavement structures slightly reduces the CO emission. The results comparing the low-grade mixtures with the high-grade mixtures indicate that the NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems of the low-grade mixture is 2.95%, 2.95%, and 2.95% lower than the NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems of the high-grade mixtures, respectively. It is concluded that the effect of mix design on CO gas emission is higher than the effect of RCA replacement.

3.8. Hg

Fig. 10 indicates the normalized values of Hg generation of the NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems for low- and high-grade concrete mixtures. Results of the low-grade mixture indicate that the Hg generation of the NA/NA system is 0.25%, 0.39%, and 0.52% lower than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems, respectively. Regarding the high-grade mixture, the NA/NA system generates less Hg than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems by 0.51%, 0.26%, and 0.13%, respectively. The NA/NA system slightly generates less Hg than the subbase and wearing course layer that contains RCA. Comparing results between the low-grade with the high-grade mixture, the Hg generation of the low-grade mixture is in the range between 3% and 4% lower than the high-grade mixture. Selecting suitable mix design for each application significantly reduces the Hg generation. The proper concrete mix design selection results in reduced Hg generation at higher degrees than the RCA replacement in concrete.

3.9. Pb

The Pb hazardous characteristics from concrete pavement structure is assessed using a Toxicity Characteristic Leaching Procedure (TCLP). Waste material such as RCA is categorized as a toxic substance when the contaminants has a concentration value reported in the TCLP higher than the regulatory limit [62]. Nevertheless, in a typical concrete, the Pb generation shall not exceed the US EPA regulation level of 5 mg/L [63]. In general, the issue of Pb generation from concrete is not present as a serious environmental problem. The normalized values of the water consumption of the NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems for low-grade and high-grade concrete mixtures are shown in Fig. 11. Results indicate that Pb generation of the NA/NA system for the low-grade mixture is 0.37%, 0.51%, and 0.66% higher than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems, respectively. Regarding the high-grade mixture, alike the results from the low-grade mixtures, Pb generation of the NA/NA mixture is 0.37%, 0.51%, and 0.65% higher than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems, respectively. This indicates that adding the RCA in either subbase or wearing course layer results in the reduction of Pb generation. When comparing Pb generation of the low-grade with the high-grade mixture, the results exhibited that the low-grade mixture generates less Pb than the high-grade mixture by about 4.5% for all systems. Results here indicate that the implementation of concrete mixture selection suitably for each application should be emphasized.

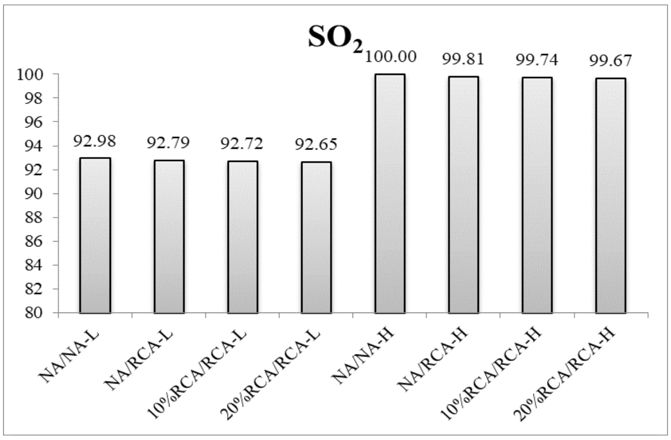

Fig. 8. Normalized SO_2 gas emission of different pavement systems and different mix designs.

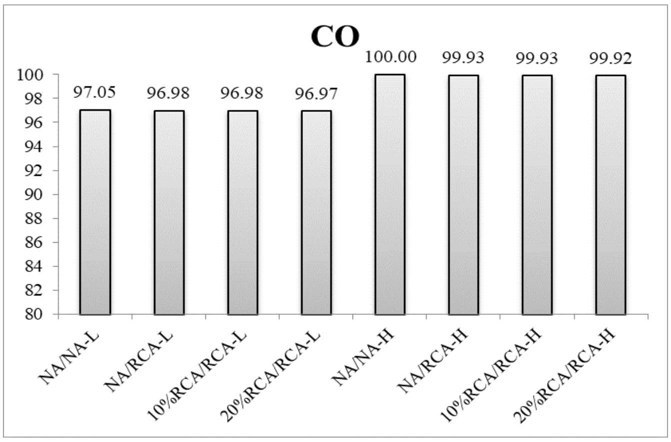

Fig. 9. Normalized CO gas emission of different pavement systems and different mix designs.

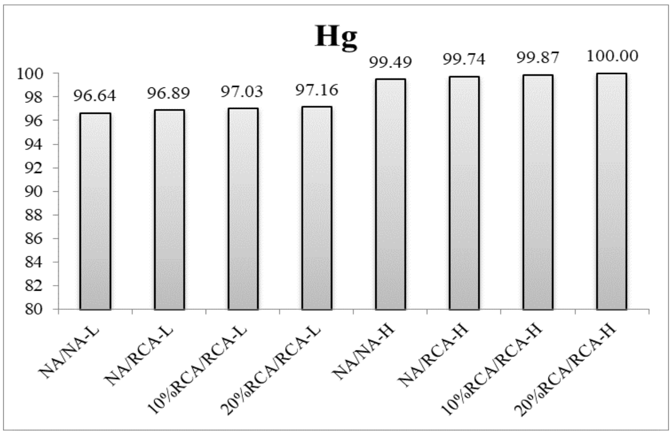

Fig. 10. Normalized Hg generation of different pavement systems and different mix designs.

3.10. RCRA hazardous waste

Fig. 12 shows the normalized values of the RCRA hazardous waste generation for different pavement systems and different concrete mixtures. Results of the low-grade mixture indicate that the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems have 0.46%, 0.84%, and 1.22% higher in RCRA hazardous waste generation than the NA/NA system, respectively. The results of the high-grade concrete mixture exhibited similar results with the low-grade concrete mixture. The NA/NA system for the high-grade mixture generates RCRA hazardous waste 0.37%, 0.72%, and 1.20% less than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems, respectively. For both low-grade and high-grade mixtures, using the RCA in either subbase or wearing course layer slightly increases the amount of RCRA hazardous waste. Comparing the results of the low-grade mixture with the high-grade mixture, RCRA hazardous waste generation of the low-grade mixture for the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems is 0.28%, 0.287%, 0.27%, and 0.26% lower than the high-grade

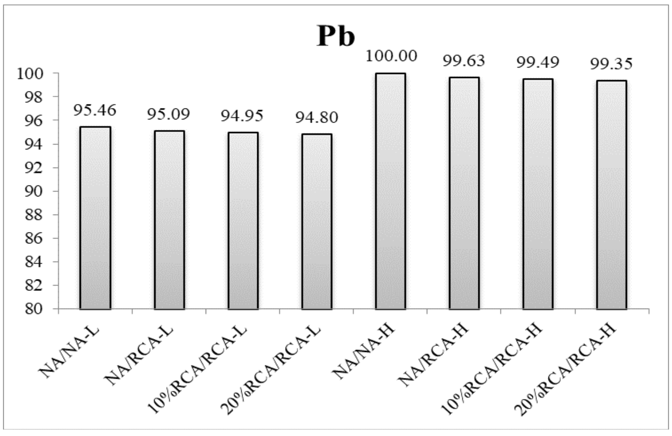

Fig. 11. Normalized Pb generation of different pavement systems and different mix designs.

mixture, respectively. The selection of the mix design can result in slight reduction of RCRA hazardous waste generation. Both adding RCA in concrete mixtures and adjusting concrete mix design seem to have a slight effect (less than 1%) on RCRA hazardous waste generation.

3.11. Human toxicity potential (cancer)

A calculated index that reflects the potential harm of a unit of chemical released into the environment, is defined as human toxicity potential. It is based on both the inherent toxicity of a compound and its potential dose of benzene equivalence to create carcinogens [64]. The normalized values of human toxicity potential associated with cancer of the NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems for low-grade and high-grade concrete mixtures are shown in Fig. 13. Results of the low-grade concrete mixture indicate that the human toxicity potential of cancer of the NA/NA system is 6.79%, 6.30%, and 5.81% lower than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems, respectively. Regarding the high-grade concrete mixture, the NA/NA system produces less human toxicity potential (cancer) than the NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems by 6.78%, 6.31%, and 5.83%, respectively. For both grades, the NA/NA system have the least potential to make humans cancer. It is believed that the use of RCA in subbase leads to the highest potential for carcinogens. This is due to the potential of recycled material that can be leached and closer distance of recycled material in the subbase layer to the ground water can generate more toxicity potentials [65]. Comparing the results between the low-grade with the high-grade mixture, the human toxicity potential (cancer) of the low-grade mixture is in the range between 0.65% and 0.68% higher than the high-grade mixture. In the cases of human toxicity potential to carcinogens, RCA replacement in pavement structure has greater impact, when compared to the mix design selection.

3.12. Human toxicity potential (Non-cancer)

The total emission of human toxicity potential associated with non-carcinogens is assessed regarding toluene equivalents [66]. Their results of the normalized values of the NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems for low- and high-grade concrete mixtures are shown in Fig. 14. Results indicate that human toxicity potential of non-cancer of the NA/NA system is 5.52% and 0.58% less than the NA/RCA and 10% RCA/RCA systems, respectively, but 4.36% higher than the 20% RCA/RCA system. In regards with the high-grade mixture, results exhibited the similar manner of which the NA/NA system has 5.52% and 0.71% less potential to create non-cancer toxic than the NA/RCA and 10% RCA/RCA systems, respectively, but 4.36% higher than the 20% RCA/RCA system. As discussed earlier, the use of RCA in subbase could result in the highest harmful potential due to its leachate in vicinity of groundwater. The effect of replacing NA with RCA in wearing course layer significantly reduces its potential. When comparing the results between low-grade and high-grade concrete mixture, it is found that the NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems for the low-grade concrete mixtures has higher potential to create the human toxicity potential of non-carcinogens than the NA/NA, NA/RCA, 10% RCA/RCA, and 20% RCA/RCA systems of the high-grade mixtures by 1.92%, 1.92%, 1.79%, and 1.66%, respectively. The use of RCA in wearing coarse layer leads to higher on human toxicity potential of non-cancer than the concrete mix design selection.

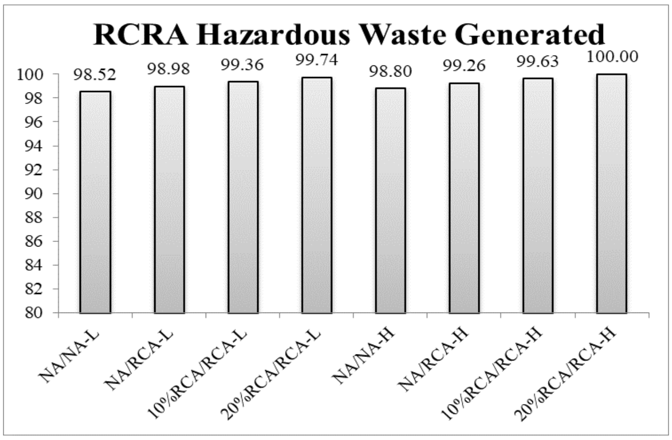

Fig. 12. Normalized RCRA hazardous waste generated of different pavement systems and different mix designs.

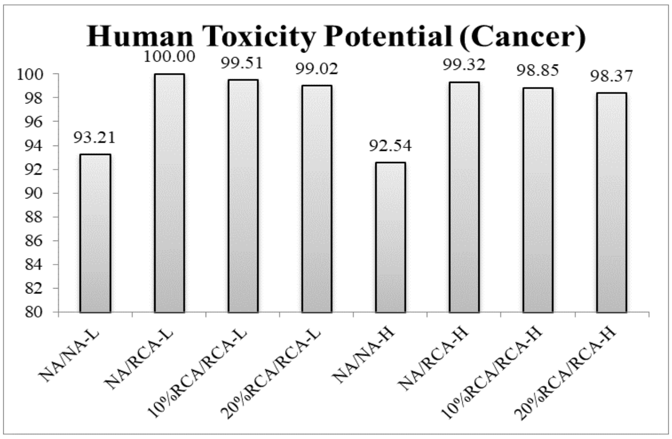

Fig. 13. Normalized human toxicity potential (cancer) of different pavement systems and different mix designs.

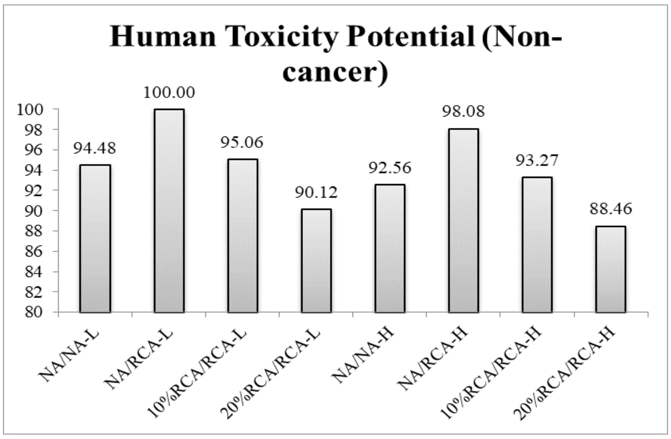

Fig. 14. Normalized human toxicity potential (non-cancer) of different pavement systems and different mix designs.

4. Discussion

Table 5 indicates the summary of the effect of using 100% RCA in subbase and 20% RCA in wearing course layer in concrete pavement structure. Results in the table exhibited that the use of RCA in pavement structure at 100% replacement level for subbase and 20% replacement level for wearing coarse layer resulted in the positive impact on energy consumption, water consumption, CO_2 gas emission, PM10, RCRA hazardous waste generation and the slightly positive impact on SO_2 and Pb generation. Whereas, it resulted in the negative environmental impact on NO_x, human toxicity potential (cancer), and human toxicity potential (non-cancer), and the slightly negative impact on CO and Hg generation. The environmental performance comparison for concrete with different mix designs are summarized in Table 6. The environmental impact performance of the high-grade mixture that is greater than the low-grade more than 1% includes the energy consumption, the water consumption, the CO_2 gas emission, the NOx, the SO_2, the CO, the Hg, and the Pb generation. The environmental impact performance of the high-grade mixture that is greater than low-grade mixture ranging from 0% to 1% includes the PM10 and the RCRA hazardous waste. However, for the negative environmental impact, the human toxicity potential (non-cancer) of the low-grade mixture is 1% higher than the high-grade mixture and the human toxicity potential (cancer) of the low-grade mixture is in the range of 0% to 1% higher than the high-grade mixture.

This study mainly determines the LCA during the material production and construction phases. The RCA production and NA production processes are different depending on the locations of materials associated. The construction of the solid pavement structure is replaced by RCA at 10% and 20% and this does not significantly reduce the performance characteristics of the structure. Therefore, the maintenance phase is alike for both NA and RCA structures. In addition, the service life is equaled for both cases. If the replacement level of RCA increases (e.g., greater than 30%), the performance of the RCA structure will likely have lower quality than the NA structure; hence, the maintenance and end-of-life phases in the LCA study are required to revise. Nonetheless, the material cost is not explained in this paper. If the material cost is one of the key factors for contractors to select the material used in the pavement structure, the RCA will be not cost-competitive at all when compared to the NA. The material cost of RCA in Thailand is about 25 to 30 USD/ton; whereas, the material cost of the NA is only 10 to 15 USD/ton. This is still very challenged issuefor aggregate producers in developing countries to shift the use o f NA to RCA. The supportive campaign from a government agency of utilizing the recycled materials is needed and this has been in place in many developed countries such as in Japan and E.U. where there is the extra cost if the C&D wastes are discardsed to public and are not recycled back into the concrete structure. This ends up for RCA to have a potential for economically competitiveness.

Table 5
Summary of environmental performance effect of using 100% RCA in subbase and 20% RCA in wearing course layer in concrete pavement structure.

Effect	Degree	Environmental performance
Positive	> 1%	Energy Water CO_2 PM10 RCRA hazardous waste
Positive	0-1%	SO_2 Pb
Negative	0-1%	CO Hg
Negative	> 1%	NO_x Human toxicity potential (cancer) Human toxicity potential (Non-cancer)

Table 6
Environmental performance comparison between low- and high-grade concrete mixtures.

Effect	Degree	Environmental performance
High-grade > Low-grade	> 1%	Energy Water CO_2 NO_x SO_2 CO Hg Pb
High-grade > Low-grade	0-1%	PM10 RCRA hazardous waste
Low-grade > High-grade	0-1%	Human toxicity potential (cancer)
Low-grade > High-grade	> 1%	Human toxicity potential (Non-cancer)

5. Conclusions

RCA used in many developing countries has been normally dumped to the landfill. To broaden its use in high-value applications, performing the LCA study of the pavement structure containing RCA can be beneficial to emphasize to reduction of environmental impacts. Results here present frontier information for users to utilize RCA in lieu of NA and the influence of concrete mix design calculated from the LCA method. The results found can be concluded that:

1. When using 20% replacement of RCA in concrete wearing course layer along with the use of traditional 100% RCA in subbase layer compared to the 100% NA pavement structures, results indicated that the energy consumption, water consumption, CO_2 gas, PM10, and RCRA waste generation reduced more than 1%. The SO_2, Pb, CO, and Hg emissions were unlikely to change. But, the NO_x emission and human toxicity potential for carcinogens and non-carcinogens increased more than 1%.
2. Using the low-grade concrete mix design could reduce the environmental impacts including energy consumption, water consumption, CO_2, NO2, SO2, CO, Hg, and Pb emissions more than 1%. The PM10, RCRA hazardous waste emissions, and human toxicity potential for carcinogens were influenced by changing the concrete mix design lower than 1%. Only human toxicity potential for non-carcinogens could have the negative environmental impact when using high-grade concrete mix design.

The concrete mixture of 100% RCA in subbase and 20% RCA in wearing course layer with lower grade concrete mix design presents significant reduction of environmental performance in this study. It is clearly seen that using higher %RCA replacement levels and less cement contents in concrete mixture tremendously lowers the environmental impacts when making pavement structure. Mix design selection for the suitable application is one of the keys to reduce environmental impact in pavement structure.

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