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Life cycle assessment, mechanical properties, and durability of roller compacted concrete pavement containing recycled waste materials

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Abstract

This study focused on the environmental life cycle assessment of roller compacted concrete pavement (RCCP) containing ceramic waste aggregate and coal waste powder. Also, the mechanical and durability properties of RCCP were tested. 10, 15, 20, and 25% ceramic waste aggregates, by the weight of coarse aggregates, were used as replacements for natural aggregates. Moreover, coal waste powder was used in the mixture at the replacement levels of 4 and 8% by the weight of cement. The results showed that the use of ceramic waste as aggregates increased the vibrating compaction time of fresh mixtures while decreasing their density. Furthermore, coal waste powder reduced the vibrating compaction time of RCCP mixtures. The life cycle assessment method showed that using these materials reduced greenhouses gases, and 15% of ceramic waste aggregate and 8% of coal waste powder declined greenhouses gases by 10%. Also, this combination of ceramic waste aggregate and coal waste powder showed the highest positive impact on the global warming index, reducing by 9 %. Moreover, the microstructural analysis of concrete was performed by SEM images, and the durability of RCCP was measured. The results showed that after replacing 15% natural aggregates with ceramic waste, 90-d compressive, splitting tensile and flexural strengths were increased by 14, 39, and 20%, respectively. Also, using ceramic waste aggregate increased the durability of concrete after 90-d curing time. Overall, using these waste materials in RCCP can not only reduce emissions and global warming issues but can enhance the mechanical properties of RCCP and recycle plenty of waste materials.

Keywords: Life cycle assessment; Global warming index; Mechanical properties; Durability; Recycling; Roller compacted concrete pavement

1. Introduction

In recent years, numerous researchers have focused on recycling strategies due to the increasing rate of industrial wastes. Meanwhile, roads have been widely explored because of playing a remarkable role in the development of countries. One type of concrete pavement known as roller compacted concrete pavement (RCCP) is a mixture of aggregates, cement, and water with zero-slump. First, this mixture is performed by using a conventional paving machine for asphalt and then will be compressed and compacted by a vibratory roller. The RCCP is mainly used in factory premises, mine access roads, port areas, military vehicle terminal, car parking lots, warehouse floors, airport hangars, roads, and low- or medium-speed streets [1].

Nowadays, researchers have acknowledged the importance of recycling the industrial waste essential for reducing landfills along with the need to use natural aggregates, thereby preventing damages to the environment. Industrial waste materials are used in concrete pavements as an alternative to natural aggregates and also as a partial replacement for cement. In addition to its favorable environmental advantages, this method can reduce the cost of concrete production.

Cement production also requires input energy (850 kcal/kg of clinker) and a considerable amount of natural raw materials (1.7 tons of rock for producing 1 ton of clinker). Also, the production of every ton of cement, including the essential fuel consumption, leads to the emission of roughly 94 tons of CO_2 [2]. Therefore, industrial wastes, used as a substitute to replace the cement partially, can reduce the environmental impacts caused by cement production.

The improvement of sustainable advancement of road pavement has grabbed researchers' attention because this segment is responsible for high energy consumption and environmental damages, particularly concerning the utilization of raw materials, improper waste removal, and greenhouse gas emissions [3].

The activities engaged in construction processes are the primary causes of the exhaustion of natural resources, representing 24% of the extraction of natural resources on a worldwide scale, and they are additionally the critical waste generators. Also, the consumption of natural resources and the raw material extr including landscape damage, biological system corruption, harm to human health, and the pollution of soil, water, and air [4].

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Regarding these environmental damages, it is logically realized that the civil construction area is the significant reason for greenhouse gas emissions, being responsible for around 40–50% of the world's greenhouse gas emissions [5]. Contamination gases are discharged into the air through the construction processes, including the transportation of materials, the energy utilized by machinery in preparing and assembling of construction materials [6].

Concrete is one of the significant consumers of natural resources and CO_2 producers. Concrete presents a severe problem to the environment because of the high emissions related to the production of a unit volume and the vast amounts required to support current society and improve ways of life. For instance, the worldwide production of cement was evaluated to be between 13 and 21 billion tons in 2009. With a consolidated increment in populace development and urbanization, it is anticipated to keep on rising [7]. Therefore, the construction industry consumes half of the raw materials, 40% of all energy produced, and creates practically half of worldwide waste streams [8].

A huge amount of ceramic waste is produced annually by ceramic factories. Since the ceramic wastes are mostly deposited in landfills, finding a solution for recycling the ceramic wastes is essential. The ceramic waste production rate in Europe ranges from 3 to 7% [9]. For instance, according to the Portuguese Center of Ceramic and Glass, the amount of waste generated by sanitary ceramic factories was about 10,000 tons in 2012. Besides, a large amount of ceramic waste is produced annually due to the demolition or reconstruction of buildings, thereby increasing the landfill area around the world [10].

Life cycle assessment (LCA) is a method that can investigate the energy flow, materials, and the environmental impacts of products during their manufacturing and service lives. This approach can show the environmental benefits of a construction project.

2. Literature review

The usage of waste materials, including ceramic waste, coal waste, XLPE waste, crumb rubber, recycled concrete aggregates, and recycled polyethylene terephthalate (PET), was investigated in rigid and flexible pavements in recent years. In a study conducted by Fakhri and Saberi (2016), the aggregates and a portion of cement were replaced by the crumb rubber and silica fume, respectively. Various crumb rubber percentages (5, 10,..., and 35%) along with 8% silica were used to examine the mechanical properties of RCCP mixtures. The results showed an increase in the 28-d compressive strength of specimens containing 5, 10, 15, and 20% of crumb rubber as well as silica fume [11]. In addition to the crumb rubber, some other waste materials such as recycled concrete aggregate (RCA), construction waste, and reclaimed asphalt pavement (RAP) were used as aggregates of concrete pavement. The results indicated that using these materials not only has environmental benefits in terms of waste management, but these materials could enhance the mechanical properties of concrete pavement when they were used in suitable percentages [12-14].

Also, shredded rubber was used as aggregates of RCCP in two other studies. Different percentages of this material were substituted with natural aggregates, and the mechanical properties of RCCP were investigated. The test results showed that this material could enhance the energy absorption and ductility of RCCP. However, this material declined the mechanical properties of RCCP. So, silica fume was added to RCCP mixtures to alleviate this problem [15,16]. Also, Shamsaei et al. (2017) investigated the effect of cross-linked polyethylene (XLPE) waste as recycled aggregate (5, 15, 30, and 50% of replacement) in RCCP, and the mechanical properties of RCCP mix were examined. The results indicated that XLPE waste increased the ductility of RCCP [17].

Moreover, Lopez-Uceda et al. (2016) investigated the effect of using recycled concrete aggregate (RCA), as coarse aggregates, on the mechanical properties of roller compacted concrete (RCC). The replacement was conducted by 50 and 100% contents. Based on the obtained results, the 100% replacement of coarse aggregate with RCA was recommended to be used in the construction of roads [18]. In another study, Shamsaei et al. (2019) investigated the impact of using coal and ceramic waste powders as a partial substitute of cement in RCCP, and the percentages of substitution were 5 and 10 by weight. The test result showed that the mechanical properties of RCCP were declined [19]. Moreover, ceramic waste, micro-silica, and wollastonite were used in concrete mixtures to investigate the mechanical and durability properties. Ceramic waste was replaced with partial amounts of natural aggregates, and wollastonite and micro-silica were replaced with a partial amount of cement. The durability of concrete was examined under different temperatures from 20°C to 800°C and against the acid environment. The test results indicated that using ceramic waste enhanced the durability of concrete mixtures [20] Also, the freeze-thaw resistance of concrete mixes, containing ceramic waste as fine aggregates, was examined. Different percentages of ceramic waste, including 20%, 40%,…, 80%, and 100%, were substituted with fine aggregates. The result revealed that using ceramic waste could enhance the durability of concrete mixes [21].

In addition to the studies related to using ceramic waste in concrete pavements, ceramic waste powder and other materials, including recycled PET, Gilsonite, and Sasobit, were used as raw materials of asphalt pavement [22,23]. Shamsaei et al. (2020) evaluated the impacts of ceramic waste powder on hot mix asphalt. This waste material was used as filler in different percentages of 25, 50, 75, and 100%, and the test results revealed that this material enhanced the performance of hot mix asphalt [24].

Some studies focused on the LCA and the environmental impacts of waste materials used as aggregates and a partial replacement for cement in concrete mixtures. Kurda et al. (2018) evaluated the environmental effects of concrete mixes, which contained fly ash (FA) and reused concrete aggregates (RCA), with and without Superplasticizer (SP). The result indicated that the environmental effects were marginally expanded when SP was utilized. However, the environmental impacts were diminished when coarse aggregates were completely substituted with RCA. Despite the long transportation distance between the coal power plant and the concrete plant considered in the case study, the environmental effects were declined with the expansion of FA [25].

In another study, Estanqueiro et al. (2016) investigated the LCA of both natural and reused coarse aggregates production. The utilization of these aggregates for concrete production was much better than natural aggregates [26]. Furthermore, Jiang et al. (2014) examined the LCA of glass powder, alkali-activated slag concrete, and mortars. The result indicated that a 35-MPa alkali-activated slag concrete has 73% lower greenhouse gas emissions, 43% less energy, 25% less water, and 22–94% lower impacts for all environmental toxicity classes except for a 72% higher ecotoxicity impact. The paper infers that utilizing elective cementitious materials, glass powder, and alkali-activated slag as cement substitutions could fundamentally decrease the environmental effects of cement-based items [27].

According to the background of using waste materials in RCCP, it is evident that the environmental LCA of using ceramic waste aggregate (CWA) and coal waste powder (CWP) in RCCP has not been conducted yet. Also, using CWA in RCCP can influence the workability of this type of concrete pavement, which demands a comprehensive investigation. In this study, Firstly, the vibrating compaction time (VeBe time), density, workability, mechanical properties, and durability of RCCP containing these waste materials are investigated. The LCA is then evaluated to calculate the amounts of emissions and their impacts on global warming.

3. Methodology and materials

3.1. Materials

Some materials were used to construct RCCP in this study, including water, coarse limestone aggregates, sand, and Portland cement type II. The limestone-based aggregates were supplied from a mine in Shahrood city in Semnan province. Besides, crushed sand, used as fine aggregates, was provided from Miami city in Semnan province. The glazed ceramic wastes were supplied from the Semnan Ceramic Factory, while the coal waste was gathered from the landfill of a coal mine called Central Alborz Coal Company in Semnan province. In this study, RCCP mixes containing ceramic wastes, used as coarse aggregates in different sieve sizes (passing the 19mm, 12.5mm, and 9.5mm sieves), were examined. Moreover, the CWP was also used as a partial replacement of cement in RCCP (passing the No. 200 sieve). Different sizes of ceramic and coal waste materials are depicted in Fig. 1.

According to the RCCP guide, the value of concrete slump is zero [1,28]. Moreover, the maximum size of coarse aggregates is 19 mm, while the recommended limits for the gradation are in accordance with ACI 211.3R [28]. Also, the amount of cement was approximately 15% of the total mass of aggregates [1,29]. The gradation curve of the aggregates is depicted in Fig. 2. Furthermore, the properties of cement are reported in Table 1, and the chemical compositions of ceramic and coal waste, obtained from the XRF test, are also presented in Table 2. Besides, the physical features, along with the corresponding tests used for waste materials and natural aggregates, are listed in Table 3.

3.2. Experimental tests

The concrete mixture design was developed based on the RCCP codes [1,28]. Besides the reference control (RC) considered as the control mix design, twelve other mix designs were made, in which the natural aggregates and cement were replaced with CWA and partially with CWP, respectively. For instance, 10CWA-4CWP represents the 10% replacement of aggregate with ceramic waste and 4% replacement of cement with coal waste, respectively. Also, two methods, called the soil compaction and optimum workability, are used to calculate the mix design of RCCP. However, in this study, the optimum workability method was used for the assessment of the mix design of RCCP. The volume of ater was 159 kg/m^3 for all mixes. The mix designs are shown in Table 4. Also, the ASTM C143 was used for the slump test, and the ASTM C1170 was utilized to achieve the VeBe time and density of RCCP [36,37].

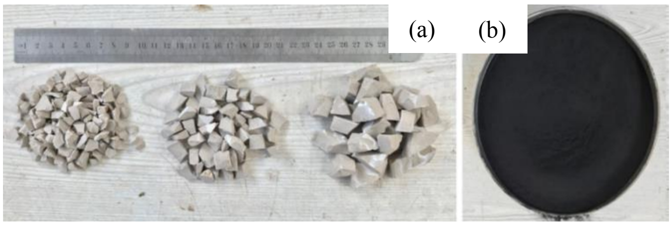

Fig. 1. (a) Ceramic waste aggregate in different sizes and (b) Coal waste powder.

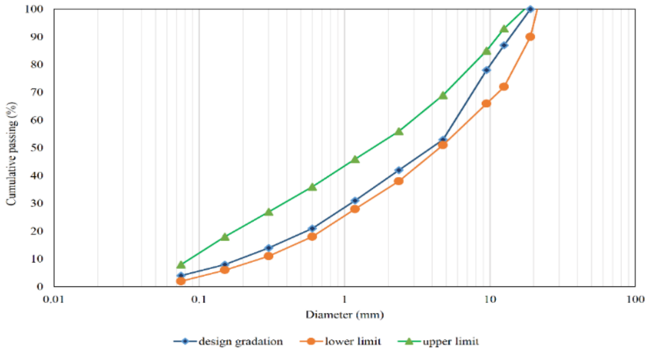

Fig. 2. Aggregate size limits.

Table 1
Physical, chemical, and mechanical properties of Portland cement type II.

Chemical compositions (%)	
Calcium oxide (CaO)	63.21
Silicon dioxide (SiO_2)	21.13
Alumina (Al_2O_3)	4.47
Ferric oxide (Fe_2O_3)	3.61
Magnesium oxide (MgO)	1.61
Sulphur trioxide (SO_3)	2.49
Sodium oxide (Na_2O)	0.41
Loss on ignition (LOI)	1.27
Other	1.8
Physical characteristics	
Specific gravity (g/cm^3)	3.21
Specific surface (cm^2/g)	3411
Soundness (%)	0.06
Initial setting time (min)	135
Final setting time (min)	220
Compressive strength (MPa)	
3-d	28.1
7-d	38.4
28-d	47.8

Table 2
Chemical compositions of ceramic and coal wastes.

Chemical composition (%)	Coal waste	Ceramic waste
SiO_2	19.65	70.23
Al_2O_3	8.1	16.1
Fe_2O_3	1.51	4.1
MgO	0.44	1.39
TiO_2	0.79	0.6
Na_2O	0.07	1.25
CaO	0.19	3.65
P_2O_5	0.16	0.31
K_2O	1.61	1.81
LOI	67.48	0.56

Table 3
Physical properties of waste materials and natural aggregates.

Properties	Standard	Sandstone	Coal waste	Limestone gravel			Ceramic waste		
				3/8	1/2	3/4	3/8	1/2	3/4
Specific gravity (kg/m³)	ASTM C127 [30] ASTM C128 [31]	2590	2695	2701	2689	2658	2288	2277	2284
Sand equivalent (%)	ASTM D2419 [32]	78	-	-	-	-	-	-	-
Fineness modulus	ASTM C33 [33]	2.89	-	-	-	-	-	-	-
Water absorption (%)	ASTM C127 [30] ASTM C128 [31]	2.1	-	0.69	0.41	0.49	1.97	1.63	1.73
Los Angeles (%)	ASTM C131 [34]	-	-	24	22	22	20	20	20
Compressive strength (kg/cm2)	BS 812-3 [35]	-	-	772	792	801	620	635	648

Table 4
Mix designs and replacement amounts of ceramic and coal wastes.

Mix	Constituents (kg/m³)								
	Cement	Sand	Coal waste	Natural gravel			Ceramic waste		
				3/8	1/2	3/4	3/8	1/2	3/4
RC	300	781	-	657	234	337	-	-	-
10CWA	300	781	-	591.3	210.6	303.3	65.7	23.4	33.7
15CWA	300	781	-	558.45	198.9	286.45	98.55	35.1	50.55
20CWA	300	781	-	525.6	187.2	269.6	131.4	46.8	67.4
25CWA	300	781	-	492.75	175.5	252.75	164.25	58.5	84.25
10CWA-4CWP	288	781	12	591.3	210.6	303.3	65.7	23.4	33.7
10CWA-8CWP	276	781	24	591.3	210.6	303.3	65.7	23.4	33.7
15CWA-4CWP	288	781	12	558.45	198.9	286.45	98.55	35.1	50.55
15CWA-8CWP	276	781	24	558.45	198.9	286.45	98.55	35.1	50.55
20CWA-4CWP	288	781	12	525.6	187.2	269.6	131.4	46.8	67.4
20CWA-8CWP	276	781	24	525.6	187.2	269.6	131.4	46.8	67.4
25CWA-4CWP	288	781	12	492.75	175.5	252.75	164.25	58.5	84.25
25CWA-8CWP	276	781	24	492.75	175.5	252.75	164.25	58.5	84.25

3.2.1. Microstructural analysis

Regarding the microstructural analysis, SEM images were used to investigate the effect of CWA and CWP on RCCP by the FEI NOVA NanoSEM 450 device. After 28-d curing, specimens were cut into 10 mm × 10 mm × 10 mm sample sizes. For achieving smooth surfaces, these samples were ground and prepared for microscopic investigation.

3.2.2. Compressive strength test

This study involved the cylindrical molds of 10 cm in diameter and 20 cm in height. The loading rate complied with ASTM C39 at 0.3 MPa/s [38]. Three layers were poured in each mold, and these layers were compacted by the surcharge mass of 50 g/cm^2. Compaction on the vibrating table with the surcharge mass was continued until the surcharge mass was surrounded by a paste ring. It should be mentioned that for the compressive test, 117 main specimens were made. At the next stage, each specimen was kept in the mold for 24 hours, and the surface of each mold was covered to avoid the evaporation of moisture. After 7-, 28- and 90-d curing times, the compressive strength was measured for specimens.

3.2.3. Splitting tensile strength test

In this study, the rate of loading was about 1.0 MPa/min. The mold dimensions, the surcharge mass, and preparing procedure of specimens of splitting tensile strength tests were identical to specimens in section 3.2. Similarly, for this test, there were 117 cylindrical specimens with identical curing conditions in section 3.2. After the 7-, 28- and 90-d curing, the splitting tensile was measured for specimens [39].

3.2.4. Flexural strength test

The test was carried out to measure the modulus of the rupture. This test should be used to examine the cured specimens under moisture conditions after being immediately brought out from curing water. Rectangular molds were used, the length, width, and height of which were 35, 10, and 10 cm, respectively. Moreover, 117 beam-shaped specimens were also prepared for this test. Three layers were poured in each rectangular mold, and these layers were compacted by the surcharge mass of 25 g/cm^2 on the vibrating table. The specimens were similarly kept in the mold for 24 h while being covered with plastic bags. After the 7-, 28- and 90-d curing, the flexural strength test was performed on each specimen [40]. According to this standard, a four-point flexural test was applied in this study.

3.2.5. Ultrasonic pulse velocity (UPV) test

The UPV test was performed for evaluating the mechanical properties and quality of the concrete. This test was applied by Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) with regard to ASTM C597 regulation [41]. It was performed on cubic specimens with 100mm × 100mm × 100mm dimensions. All of the specimens were tested with saturated conditions after 28-d curing.

3.2.6. *Chloride ion penetrability*

According to ASTM C1202, the chloride penetrability of concrete was measured. Cylindrical specimens with 100mm in diameter and 200mm in height were prepared for this test [42]. For each percentage of this study, two sections were cut from the middle of cylindrical specimens with 50mm thickness and 100mm diameter. In this test, the resistance of concrete to the penetration of chloride ion was measured. Specimens were saturated with water, and the test was performed for 6 hours. This test was performed on 28-and 90-d specimens, and the average of three measurements for each percentage is reported.

3.3. *Life cycle assessment (LCA)*

The environmental impact of this study is evaluated by the LCA method. For using the LCA method, the amounts of energy consumption and greenhouse gases of cement production are calculated for 1 m^3 of roller compacted concrete pavement. For manufacturing concrete, some energy is needed for preparing materials such as aggregates and cement. Among all these materials, cement demands much higher energy and release more emissions. In this study, the LCA method is applied in accordance with the International Organization for Standards (ISO) 14040. This method involves four important steps, including aims and the scope of the study, life cycle inventory, evaluation of environmental effects, and the explanation of results [43].

3.3.1. *The determination of aims*

The life cycle assessment of greenhouses emissions of 1 m^3 of RCCP containing CEP and COP and is the aim of this research. Then, based on the design methods of RCCP, the amount of these emissions is calculated for an industrial pavement to show a better scale for a real project. For this purpose, the amounts of total emissions of cement production, which were released from different stages, are examined for control and test specimens. In this research, two different scenarios are considered. Firstly, the amounts of energy consumption and emission of cement production are measured for the control mix design of RCCP. Then, these amounts are measured for other mixes containing CWP and COP.

3.3.2. *The life cycle inventory (LCI)*

Experimental tests and the report of cement producer can be used for calculation of life cycle inventory (LCI). The amounts of emissions can be either measured by a detector placed on the stacks of cement plants or particular equations. In this research, the emissions analysis of the cement company of another study is used [44]. So, the measured energy consumption and gas production for cement production in the cement plant is applied. These numbers can be seen in Table 5. Also, the amounts of energy consumption and gas production for extracting 1 ton of coarse aggregates are depicted in Table 6.

Table 5
The amounts of energy consumption and emissions for cement production [44].

Gases	Thermal energy consumption (ton/day)	Electrical energy consumption (ton/day)	Extraction of raw material (Ton/day)	Total exhaust gas (ton/day)	Total exhaust gas (kg/ton)
CO_2	6365.12	488.56	26.41	6880.09	906.23
CO	3.51	9.5×10^{-4}	0.132	3.64	0.48
NO_X	16.41	0.735	0.52	17.71	2.23
CH_4	3.6×10^{-2}	1.2×10^{-2}	1.4×10^{-3}	5.0×10^{-2}	6.6×10^{-3}
N_2O	3.6×10^{-3}	1.8×10^{-3}	1.4×10^{-3}	6.7×10^{-3}	9.1×10^{-4}

3.3.3. *The evaluation of environmental effects*

Many factors, such as greenhouse gas (GHG) production, using natural resources, extracting materials, and transportation of materials, can be examined to evaluate the environmental impacts. Investigation of global warming, which can be caused by high amounts of greenhouse gas (GHG) emissions, is one of the objectives of this study. For this aim, the index of global warming is calculated by Eq. (1). In this approach, an index (grams) of CO_2 in a unit is measured. Thus, the environmental effect is assessed as the amounts of CO_2 in 100 years [43].

Global Warming Index (GWI):

$$\sum_i m_i \times GWP_i \tag{1}$$

where, m_i is the mass of index flow i; and GWP_i is the amount of CO_2 (grams) with heat-trapping potential for 100 years, which is shown in Table 7.

3.3.4. *The explanation of results*

This is the final phase of LCA in which the result is analyzed to achieve a conclusion. This part can enlighten the possible environmental impacts. Thus, the positive and negative effects can be observed in this section [43].

4. Results

4.1. *Impacts of ceramic waste aggregate on the VeBe and density of RCCP*

In this study, the vibration compaction time and density were obtained for the specimens. The density of RCCP was declined from 2510 kg/m^3 to 2406 kg/m^3 for 25CWA. The highest value of density reduction was about 4% (25CWA). The density of concrete mixtures was decreased owing to the lower specific weight of ceramic waste in comparison with limestone aggregate (Fig. 3). Moreover, the relationship between the VeBe time and the amount of ceramic and coal wastes are depicted in Fig. 4.

The ceramic waste had higher water absorption in comparison with limestone aggregates. Hence, after using ceramic waste, the free water of the concrete mixes was reduced, which caused a reduction in workability. Therefore, VeBe time was also increased. Besides, the workability of concrete was increased when the coal waste was replaced with a partial amount of cement. According to Tables 1 and 2, this could be due to limited immediate hydraulic reaction of CWP owing to its very low CaO content compared to cement. So, some free water remained in mixtures, which increased workability. This result was in agreement with other studies in which some powder was replaced by cement partially [46,47]. Thus, VeBe time was decreased in specimens containing ceramic and coal waste simultaneously, in comparison with specimens containing ceramic waste. The minimum VeBe time

Table 6
The amounts of energy consumption and emissions for preparing coarse aggregates [45].

Energy (MJ/ton)	Gases	Total exhaust gas (kg/ton)
9.8192	CO_2	49.5
	NO_2	0.0021
	SO_2	0.0036
	Particulates (unspecified)	0.0038

Table 7
The factors of global warming potential [44].

Flow (i)	GPW_i (CO_2-equivalents)
CO_2 (net Carbon Dioxide)	1
CCl_4 (Carbon Tetrachloride)	1800
CF_4 (Carbon Tetrafluoride)	5700
CCl_2F_2 (CFC 12)	10600
$CHCl_3$ (Chloroform, HC-20)	30
CF_3Br (Halon 1301)	6900
CHF_2Cl (HCFC 22)	1700
CH_4 (Methane)	23
CH_3Br (Methyl Bromide)	5
CH_3Cl (Methyl Chloride)	16
CH_2Cl_2 (Methylene Chloride, HC-130)	10
N_2O (Nitrous Oxide)	296
CH_3CCl_3 (Trichloroethane)	140

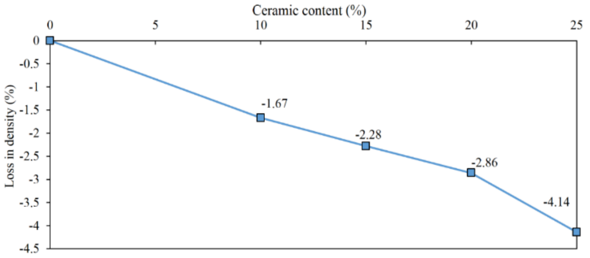

Fig. 3. Density variation after using CWA.

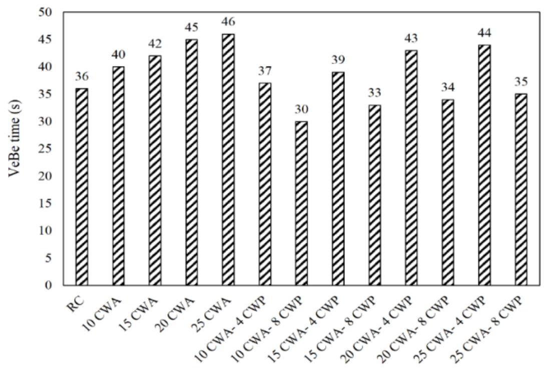

Fig. 4. The relationship between the VeBe time and amount of coal and ceramic waste materials.

was about 30s for 10CWA-8CWP, while the maximum VeBe time was about 46s for 25CWA.

4.2. *Microstructural analysis*

The SEM images of control and specimens containing CWA are depicted in Fig. 5. As can be seen in Fig. 5 (b), the CWA particle is covered by cement pastes effectively. Interfacial Transition Zone (ITZ) between the CWA and cement paste is depicted with a 4000x magnification. As can be seen, the ITZ between CWA and cement paste was thicker than natural aggregates. This larger thickness revealed the stronger bond between ceramic aggregates and cement paste in comparison with ITZ of natural aggregate. Higher water absorption of ceramic can improve the penetration of the cement paste and can create better ITZ.

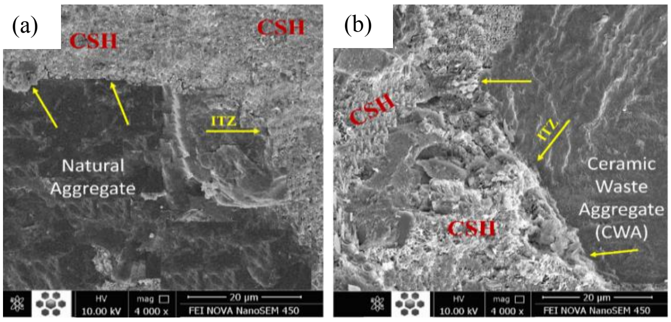

Fig. 5. SEM images of ITZ and CSH gel for (a) control and (b) specimens containing CWA.

Furthermore, the pozzolanic influence of ceramic can lead to a better quality of Calcium Silicate Hydrate (CSH), which has a significant impact on the improvement of ITZ. Fig. 5(b) shows the denser distribution of CSH gel, which covered the grater surface of the ceramic aggregate and reduced the air voids of the cement paste. The ITZ and CSH gel have substantial effects on the strength development of concrete mixes. This result is in agreement with the results of previous studies [48-50].

4.3. *Compressive strength*

Regarding 28-d specimens, apart from control specimens, the compressive strength of 10, 15, and 20% CWA, 10 and 15% CWA with 4CWP, 15CWA-8CWP, and 20CWA-4CWP were higher than the minimum allowable value (27.6 MPa). After 90-d of curing, the compressive strengths of 25CWA-8CWP and 20CWA-8CWP specimens were lower than the minimum allowable value. Also, using 10, 15, and 20% of ceramic waste increased the compressive strength. Regarding the results of the XRF test, the total acidic oxides of CWA, including Al_2O_3, Fe_2O_3, and SiO_2, were approximately 90 percent. This number is more than the minimum allowable amount for having pozzolanic properties (70%) based on the ASTM C618 regulation [51].

According to the SEM images shown in Fig. 5, the ITZ and CSH of the concrete mixtures containing CWA, which have strong effects on the strength of concrete, were thicker and denser. Thicker ITZ covered the aggregates, and the denser distribution of CSH reduced the air voids [50]. Therefore, the increase of compressive strength (10, 15, and 20CWA) can be because of the pozzolanic properties of CWA on ITZ and CSH of concrete mixtures.

As ceramic waste was increased up to 25%, the compressive strength was decreased, which can be attributed to the lower compressive strength and resistance to the Los Angeles abrasion test of ceramic waste compared to natural aggregates. Indeed, the tests conducted on ceramic waste and natural aggregate revealed that the mechanical properties of natural aggregates were better than ceramic waste (Table 3). Moreover, the two almost flat surfaces of ceramic waste contributed to the reduction of adhesion to cement paste (i.e., the upper surface which contained a special

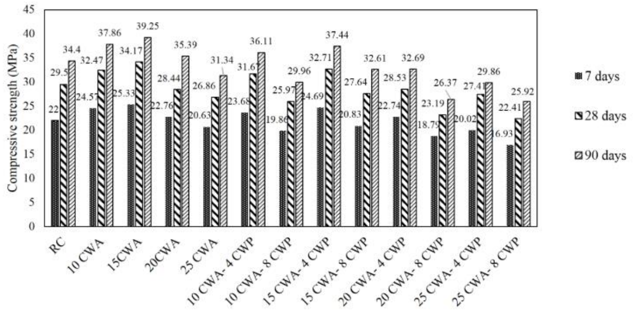

Fig. 6. The average of compressive strength for different percentages of substitution.

polished glaze and the lower surface, which was relatively flat and had low friction).

However, using CWP as a partial replacement of cement slightly reduced the compressive strength of concrete mixtures. According to the XRF test results given in Table 2 and the chemical properties of cement shown in Table 1, cement had more pozzolanic properties than coal waste, which can explain such a reduction in compressive strength. Also, the reduction in compressive strength by partially replacing cement with coal waste can be because of the lower amount of cement in the samples containing these wastes comparing the control sample. The highest and lowest compressive strengths for the 90-d curing were approximately 39.25 MPa and 25.92 MPa related to 15CWA and 25CWA-8CWP, respectively. The compressive strength of 15CWA increased by almost 14% in comparison with control specimens after 90 days of curing. The average compressive strength of the specimens after 7-, 28- and 90-d water curing is shown in Fig. 6.

4.4. *Splitting tensile strength*

The results indicated that variations of splitting tensile strength were lower compared with the compressive strength. The average of this strength was measured from 3 to 4.8 MPa after 90-d curing. In this test, 15% of ceramic waste raised the splitting tensile strength by approximately 54% and 39% for the 28- and 90-d curing, respectively. As mentioned in section 4.3, using CWA increased the quantity of CSH and improved the mechanical properties of concrete. After improving the ITZ layer, the movement of the crack during tensile loads was resisted. Therefore, the denser microstructure of concrete mixture with CWA contents enhanced the tensile strain capacity of the mixture. In addition, the tensile strength was improved. This result is in agreement with previous findings [49,50].

Overall, such an increase can be associated with the pozzolanic nature of ceramic particles, similar to the compressive strength test; thereby, increasing the splitting tensile strength in concrete containing CWA contributed to the angular shape of ceramic particles. As the ceramic waste increased to 25%, the splitting tensile strength reduced slightly compared to the replacement of aggregates with 10, 15, and 20% CWA which can be attributed to weaker mechanical properties CWA compared to natural aggregate. And, they were related to the compressive strength and crushing values of ceramic waste and natural aggregates (Table 3).

Also, two relatively flat surfaces (upper and lower ceramic surfaces) can reduce the adhesion between ceramic waste and cement paste. In specimens containing 25CWA, the splitting tensile strength also increased in comparison with the control specimens. Using CWP as a partial substitute of cement led to the slightly lower splitting tensile strength. This reduction can be because of the lower pozzolanic materials of CWP compared to cement. The maximum and minimum tensile strengths for the 90-d curing were approximately 4.77 MPa, and 3.21 MPa resulted from 15CWA and 25CWA-8CWP specimens, respectively. The average numbers of splitting tensile strength after 7-, 28- and 90-d curing are shown in Fig. 7. The correlations between the splitting tensile and compressive strengths are depicted in Fig. 8.

4.5. *Flexural strength test*

According to the results, small variations were observed in the flexural strength of various specimens (Fig. 9). Indeed, the value of flexural strength for specimens ranged from 6 to 7.5 MPa after 90-d curing. Regarding 15CWA specimens, the flexural strength increased by approximately 20% at 90-d curing compared to control specimens. The porosity, stiffness of mortar pastes and aggregates, and adhesion between aggregates and mortar paste were important factors for higher flexural strengths. So, regarding the SEM images related to thicker ITZ layer and denser CSH, such an increase can be associated with the pozzolanic nature of ceramic particles . When 25% of ceramic waste was used, the flexural strength was slightly reduced compared to the specimens containing 10, 15, and 20% of ceramic waste. This can be attributed to the weaker mechanical properties of CWA compared to natural aggregates and two relatively flat surfaces (upper and

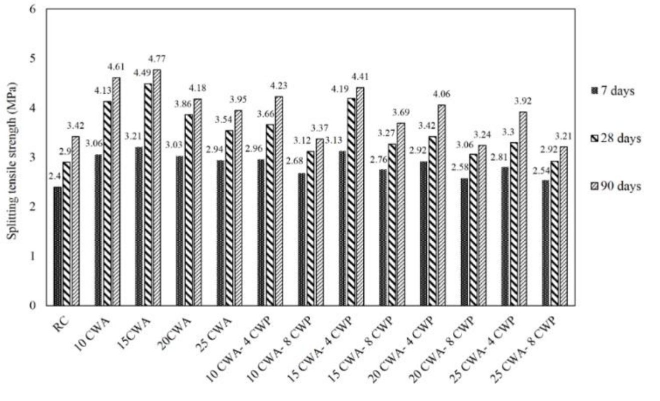

Fig. 7. The average of splitting tensile strength for different percentages of substitution.

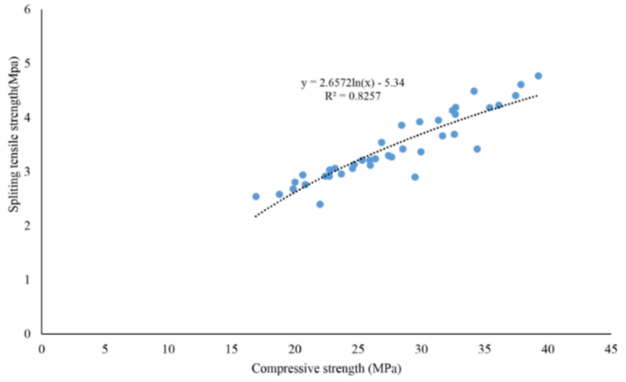

Fig. 8. The correlation of the compressive and splitting tensile strengths.

lower ceramic surfaces) that declined the adhesion to cement paste. Also, the angular shape of ceramic waste with a high percentage of usage can increase air voids [50]. These air voids had negative impacts on flexural strength. In this case, specimens containing 25% ceramic also experienced higher flexural strength than control specimens. The coal waste used as a partial replacement for cement showed slightly lower flexural strength.

According to XRF test results, this reduction can be associated with the lower pozzolanic materials of CWP compared to cement (Tables 1 and 2). The highest and lowest flexural strengths for the 90-d curing were approximately 7.25 MPa and 6.04 MPa related to the 15CWA and control specimens, respectively. The correlation between flexural and compressive strengths is depicted in Fig. 10.

4.6. Ultrasonic Pulse Velocity (UPV) test

The UPV test results of the control and specimens with waste materials are shown in Fig. 11. The test results showed that the UPV values had a direct correlation with compressive strength. The relationship of them (from 0 up to 20% CWA and 0 up to 8% CWP) is depicted in Fig. 12. Except for 25% CWA, all UPV values were more than 4500 m/s. As can be seen, the UPV of specimens containing CWA (10%, 15%, and 20%) was increased. This increase can be due to adequate ITZ surrounding aggregates and denser CSH of cement paste [52-54]. Replacing 25% of CWA with natural aggregates increased the pore space, which had a negative effect on the transmission of ultrasonic waves [55]. Using CWP as a partial cement decreased the UPV values because of its lower pozzolanic properties. And, the lower pozzolanic properties can lead to weaker CSH gel in cement paste. The most increase was observed in specimens containing 15CWA by approximately 3%, while the UPV of 25CWA-8CWP specimens reduced by 17%.

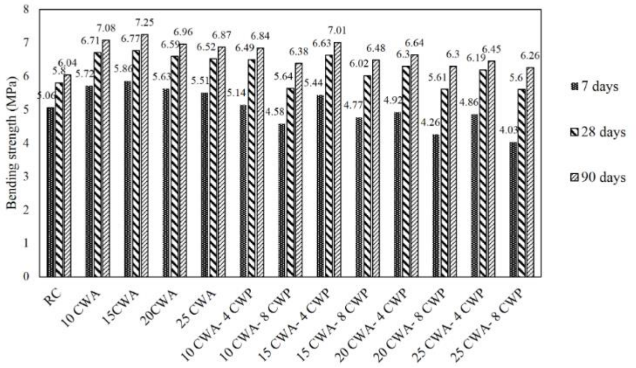

Fig. 9. The average of flexural strength for different percentages of substitution.

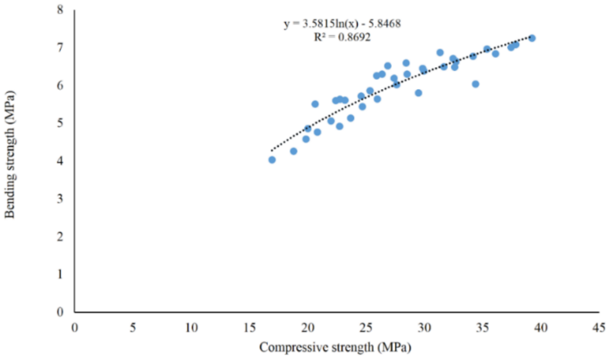

Fig. 10. The correlation between compressive and flexural strengths.

4.7. Chloride-ion penetration

The result of the chloride-ion penetration is presented in Fig. 13. As can be seen, after using CWA and CWP, the concrete resistance to penetration of ion chloride was declined for the 28-d curing time. All of the specimens except for 25CWA-8CWP were in the range of very low and low risk of corrosion based on ASTM C1202 regulation [42]. The control, 10CWA (without CWP and with 4 % CWP), and 15CWA (without and with 4 % CWP) specimens had a very low risk of corrosion (below 1000 Coulombs according to ASTM C1202) after 28-d curing [42].

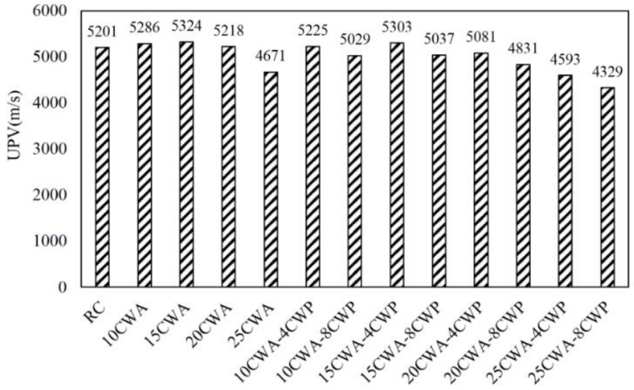

Fig. 11. The results of the UPV test after 28-d curing.

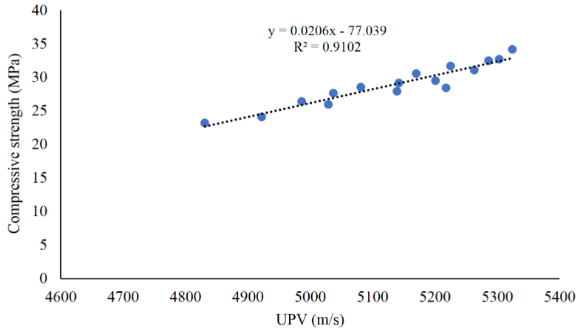

Fig. 12. The relationship between the UPV values and compressive strength for control and specimens containing waste materials.

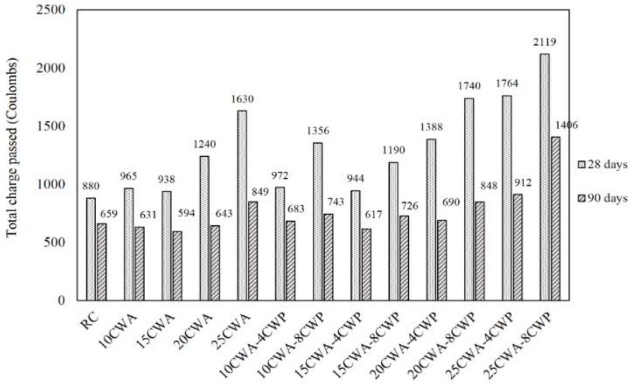

Fig. 13. The chloride-ion penetration of concrete mixtures.

The test results for 90-d curing of specimens showed that using 10, 15, and 20CWA increased the resistance of concrete specimens to the penetration of chloride ion. This is attributed to the pozzolanic effect of CWA and thicker ITZ and denser CSH. This increment for 90-d specimens can be because of adequate time for the curing process to active some pozzolanic effects. So, a dense mortar was produced by a highly hydrated cement paste, which was completely impenetrable. This was also observed by Zhutovsky and Kovler (2012) when the fine lightweight aggregates were substituted with partial amounts of natural aggregates, and the chloride penetration resistance was enhanced. Therefore, the cement hydration was improved due to the lightweight aggregate after more curing time. Also, more phases of Aft and AFm can be formed by Al_2O_3 and SiO_2, which are the highest contents of ceramic waste (almost 86 % in Table 2), which can form Friedel's salt and the mechanism of ion exchange to provide resistance against chloride ions [21,54]. This result is in agreement with the result of the previous studies in which waste materials were used in concrete mixtures [54,55].

4.8. The LCA method

For using the LCA method, the amounts GHGs of cement production are calculated for 1 m^3 control RCCP and RCCP containing different percentages of CEP and COP. According to Table 4, Table 5, and the amount of cement for each mix design, the amounts of GHSs for RCCP mixtures, that have the allowable 28-d compressive strengths, were calculated and depicted in Table 8.

As can be seen, using these waste materials in RCCP can decrease the amounts of GHGs significantly. The most reductions were observed for 15CWA-8CWP and 25CWA-4CWP specimens. For example, CO_2 production was reduced by approximately 10% and 8% for these specimens, respectively. This reduction was also observed for all other gases. As can be seen in Table 8, CO, NO_X, CH_4, and N_2O were decreased by almost 8 % for 15CWA-8CWP specimens.

4.8.1. The estimation of emissions reduction for a real project

For better understanding the amounts of emissions reduction for test specimens, a small surface was designed. RCCP can be used for different purposes. In this study, the PCA method was used to design the industrial pavement [1]. The assumptions for designing this pavement is shown in Table 9. According to the flexural strength test results, the average flexural strength is 6.5 MPa. Therefore, the thickness of the pavement was calculated by the PCA method, and Table 9 (21 cm). The surface area of this place was assumed 500 m^2, and the amounts of emissions for some mixtures are shown in Table 10. Also, to achieve an index showing the effectiveness of using these waste materials in terms of strength and air pollution reduction, the ratio of 28-d compressive strengths of different mix designs to their emissions was calculated, which is depicted in Table 11. Higher Indexes have better performance in terms of both strength and gas reduction. The results indicated that compared to other specimens, 15CWA specimens had the best performance in terms of these two factors.

Table 8
The amounts of GHGs production for 1 m^3 of RCCP.

Gases	Amounts of gas production (kg)									
	Control	10CWA	15CWA	20CWA	25CWA	10CWA-4CWP	15CWA-4CWP	15CWA-8CWP	20CWA-4CWP	25CWA-4CWP
CO_2	332.66	326.58	323.54	320.5	317.46	315.71	312.67	301.79	309.63	306.59
CO	0.144	0.144	0.144	0.144	0.144	0.138	0.138	0.132	0.138	0.138
NO_X	0.7	0.7	0.7	0.7	0.7	0.642	0.642	0.615	0.642	0.642
CH_4	0.00198	0.00198	0.00198	0.00198	0.00198	0.0019	0.0019	0.0018	0.0019	0.0019
N_2O	0.00027	0.00027	0.00027	0.00027	0.00027	0.00026	0.00026	0.00025	0.00026	0.00026

Table 9
The assumptions for designing the industrial pavement.

Variable	Value
Maximum single-wheel load	116 KN
Tire inflation pressure	0.69 MPa
Contact area	0.16 M^2
Flexural strength	6.5 MPa
Number of wheel load applications	146000
Modulus of subgrade reaction (K)	0.27 N/mm^3

Table 10
The amounts of GHGs production for an industrial pavement with an area of 500m^2.

Gases	Amounts of gas production (kg)						
	Control	25CWA	10CWA-4CWP	15CWA-4CWP	15CWA-8CWP	20CWA-4CWP	25CWA-4CWP
CO_2	34929.3	33333.3	33149.55	32830.35	31687.95	32511.15	32191.95
CO	15.2	15.2	14.49	14.49	13.86	14.49	14.49
NO_X	73.5	73.5	67.41	67.41	64.575	67.41	67.41
CH_4	0.2079	0.2079	0.1995	0.1995	0.189	0.1995	0.1995
N_2O	0.02835	0.02835	0.0273	0.0273	0.02625	0.0273	0.0273

Table 11
The comparison of mix designs in terms of the strength and emission reduction for 1 m^3 RCCP.

	The ratio of the 28-d compressive strengths to total emissions									
	Control	10CWA	15CWA	20CWA	25CWA	10CWA-4CWP	15CWA-4CWP	15CWA-8CWP	20CWA-4CWP	25CWA-4CWP
Effectiveness Index	0.088	0.099	0.105	0.089	0.084	0.100	0.104	0.091	0.092	0.093

4.9. Global warming potential

Eq. (1), and the amounts of GHGs in Table 10, were utilized to calculate the global warming index (GWI). The GWI of different RCCP mixtures is shown in Fig 14. So, the usage of these waste materials declined the GWI. The highest reduction was observed for 15CWA-8CWP specimens, which decreased the GWI by almost 9%.

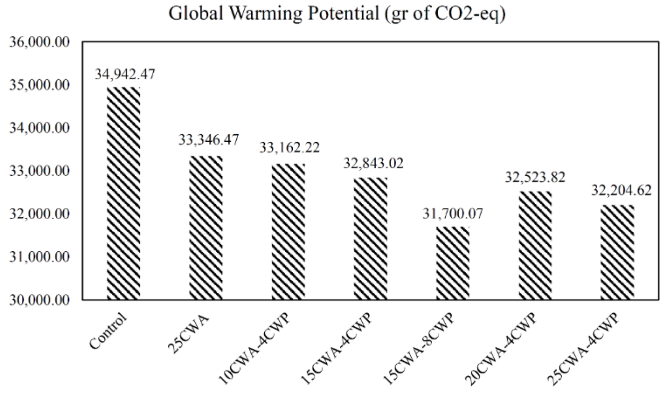

Fig. 14. The effects of using CWA and CWP on the global warming.

5. Conclusions

This study aimed to evaluate the environmental LCA, mechanical properties, and durability of RCCP containing CWA and CWP as coarse aggregates and a portion of cement, respectively. The application of ceramic waste as aggregates reduced the free water content and the workability of RCCP. However, the replacement of cement with CWP increased the workability of RCCP due to the limited immediate hydraulic reaction compared to cement. When ceramic waste was used, the density of RCCP was slightly decreased. So, density was significantly reduced when more ceramic waste was used.

The results of the LCA method revealed that using these waste materials can reduce GHGs effectively. So, the amounts of emissions for different mixtures, whose compressive strengths were higher than the lowest allowable compressive strength, were measured. The highest rates of emissions reduction were observed for 15CWA-8CWP and 25CWA-4CWP specimens, 10% and 8%, respectively. Also, 15CWA-8CWP specimens had positive impacts on global warming, and they reduced the GWI by 9%. Regarding both mechanical properties and environmental benefits, 15CWA specimens had the best performance in comparison with other samples.

Regarding the strength of RCCP, the results revealed that the ceramic waste used at appropriate percentages improved the mechanical properties of RCCP. Using 10, 15, and 20% ceramic waste as aggregates increased the compressive, splitting tensile and flexural strengths of RCCP. The microstructural analysis of specimens was performed by SEM images, and these images showed that the improvement of mechanical properties of RCCP could be attributed to thicker and high-quality ITZ and denser CSH gel in paste owing to pozzolanic properties of CWA. However, as ceramic waste was raised to 25%, the strengths values were declined.

To evaluate the quality and durability of RCCP, UPV values, and resistance of concrete to the penetration of chloride ion were tested. The result of the UPV test revealed that the UPV values had a direct relationship with compressive strength, and using 10, 15, and 20% CWA raised UPV values. Although the resistance of control specimens to chloride ion penetration after using CWA reduced for 28-d curing, this waste material increased the durability of concrete specimens after 90-d curing time. Regarding 90-d specimens with 15% of CWA, the flexural, splitting tensile, and compressive strengths were increased by 14, 39, and 20%, respectively.

Based on the obtained results, the use of 10, 15, and 20% of ceramic waste, as replacement of coarse aggregates, was estimated as the optimal recycling rate of this waste material. In comparison, the suitable percentage of cement replaced by CWP was calculated at 4%. Also, specimens containing CWA up to 20 % with 4 % CWP and 15% CWA with 8% CWP had the required compressive strengths for the main structural layer of primary and local routes.

Other mixtures, for which the flexural, splitting tensile strengths, and ductility were higher than the control specimens, can be employed for secondary roads and sidewalks. Regarding high rates of ceramic and coal waste production and their low recycling rates, it is crucial to use these waste materials in RCCP to reduce landfills and prevent their accumulation in the environment. More importantly, the use of CWA and CWP can reduce GHGs, global warming issues, the need for natural aggregates, and cement helping to preserve the resources, energy, and the environment. Therefore, the application of ceramic waste as aggregates and coal waste as a partial substitute of cement is recommended in RCCP mixtures.

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Conflicts of interest

Authors would like to declare no conflicts of interest.

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