Original Research

Mechanical and Environmental Evaluation of Concrete Mix Using Aggregates Recycled from Construction and Demolition Waste

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Abstract

Construction and demolition waste (CDW) has begun to take its toll on the environment. One option to mitigate the negative influence is to utilize CDW as recycled aggregate (RA) in concrete production. Recycled aggregate concrete (RAC) mixtures prepared by replacing natural aggregate (NA) with RA, with expansive agent (EXP) and polypropylene fiber (PPF) as additives, have been cast to study their mechanical properties and environmental impact. The results of compressive strength testing reveal that both additives, EXP and PPF, have positive effects on the mechanical properties. The microscopic analysis shows that the hydration reaction of EXP generates ettringite crystals which fill the internal pores of the concrete and increase the compactness of the concrete. Fiber can significantly improve the bonding between cement paste and aggregates, thus enhancing the deformation resistance of concrete. Environmental analysis shows that the leaching amount of heavy metals is very limited which is within 11.67% of the required value in China standard, and carbon emission of concrete with RA as aggregates and fly ash as low-carbon binder is lower than that of concrete without RA. The use of CDW recycled aggregates may significantly mitigate the environmental impact and improve the sustainability during concrete production.

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Introduction

Over the last few decades, substantial growth in economic activities is putting a continuously rising demand in construction industry [1-5]. As one of the most highly consumed construction materials, concrete is generally described as a product that consumes a great deal of natural resources. The primary ingredient of a concrete mixture by mass is aggregate [6-8]. Approximately 2700 million tons of natural aggregate (NA) are sold each year in the European Union [9]. Endless resource exploitation causes significant scarcities of natural resources in some areas. At the same time, due to the urban renewal, building aging or uncontrollable natural disasters, the demolishing of old buildings produces significant construction and demolished waste (CDW) [10, 11]. In the European Union, the output of CDW in 2016 was 932.7 million tons, accounting for 36% of the total solid waste. In the United States, this yield was close to 569.4 million tons in 2017, and in China, it is estimated to produce CDW over 1.8 billion tons per year [12]. Although such a large amount of CDW is produced, the recycling and reuse rate is still limited, resulting in large volumes of CDW being disposed of in landfills which may cause serious environmental contaminations [13]. Therefore, the need for reusing CDW is imminent and of significant concern to community [14].

To alleviate the two problems referred to above, the concrete industry has devoted substantial efforts to research and develop new concrete that utilizes recycled aggregate (RA) sourced from CDW as an alternative to NA. This possible solution would help reduce the demand for natural resources as well as the carbon emission of the construction industry [15]. However, the use of RA has an important influence on recycled aggregate concrete properties. In comparison to NA, RA has the drawbacks due to its low fragmentation resistance and high water absorption [16]. To date, RA extracted from waste concrete has been studied to evaluate its performance [17, 18]. It has been found that the loss in the physical and mechanical properties has a detrimental effect on the application of RAC.

The addition of additives, such as expansive agents, has been found to be an effective tool to improve the mechanical properties of RAC [19]. The expansion generated by expansive agents increases the concrete volume, and the concrete can generate compressive stress that counteracts the tendency of drying shrinkage and reduces the tensile stress, and therefore improves the crack resistance of concrete [20]. Moreover, the addition of discontinuous fibers into recycled aggregate concrete has been proven effective in improving its ductility, tensile strength and fracture toughness [21, 22]. Medina et al. considered that polypropylene fibers can effectively control surface crack growth and reduce water permeability and CO_2 diffusion into concrete [23]. Fly ash, a by-product obtained from coal burning industries, is mostly comprised of silicates and alumina [24, 25]. It improves the bonding between cement and aggregates and can be used as partial replacement of cement during the production of concrete [26, 27]. A judicious use of this material may enhance concrete workability. Francesco et al. considered that this replacement allows a reduction in energy consumption and carbon emissions [28].

It is also very important to understand the environmental impact of such materials [29]. Recently, life cycle assessment (LCA) has been successfully used as a promising tool for the environmental evaluation of various products [30]. According to international frameworks and guidelines, the LCA methodology quantifies natural resource consumption and pollutant emissions during the life cycle of mineral raw materials. According to previous studies, the leaching of heavy metals in RA is very limited. Knoeri et al. found that the carbon emission of recycled concretes was reduced by 30% compared with conventional concretes [31]. Collins conducted an LCA of RA used in highway and concluded that the use of RA gets great economic and environmental benefits by reducing the landfill requirements and carbon emissions [32]. Besides, Flower and Sanjayan also found that use fly ash and blast furnace slag in concrete can reduce greenhouse gas emission of concrete by around 15% and 22%, respectively [33].

The present study aims to evaluate the mechanical property and environmental impact of replacing NA with RA to improve the sustainability during concrete production. The effect on mechanical properties of RAC with different additives is also investigated. The environmental impacts, in terms of leaching of heavy metals and CO_2 emission, are examined. These findings are anticipated to provide guidance and suggestions to agency and the construction sector during the selection of materials in order to reduce the negative impact on the environment. The study could also facilitate the improved management of sustainable waste and efficient use of natural resources.

Material and Methods

Raw Materials

Aggregate

Recycled aggregates (Fig. 1) used in this study were processed from waste concrete, which was obtained by a local contractor specialized in collecting and separating CDW. The manufacturing technology of RA has several procedures including crushing of concrete waste (automated crusher), removal of ferrous materials (magnetic effect), removal of paper and other light particles (artificial wind) and removal of other contaminants like bitumen-based (first screening stage) [34]. With reference to the Chinese code JGJ52-2006 for Standard for technical requirements and test method of
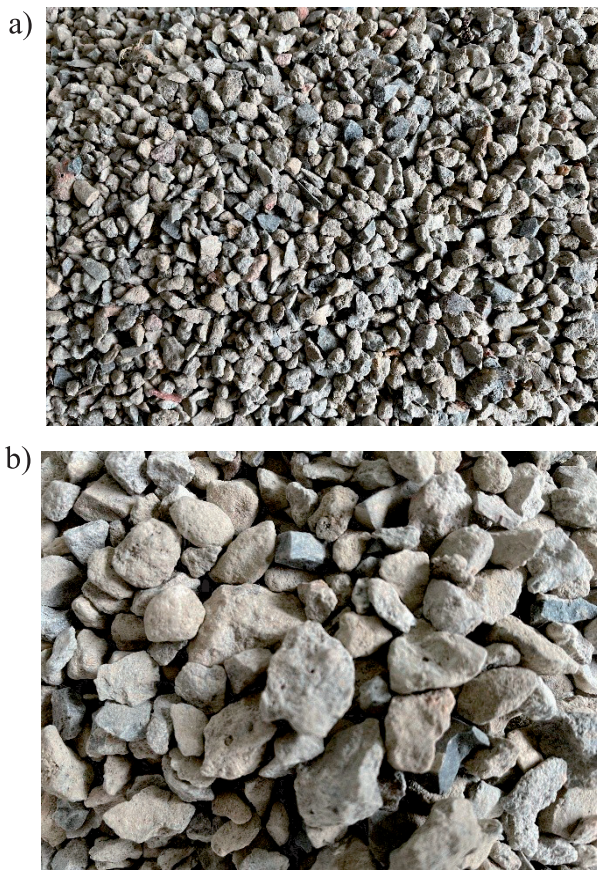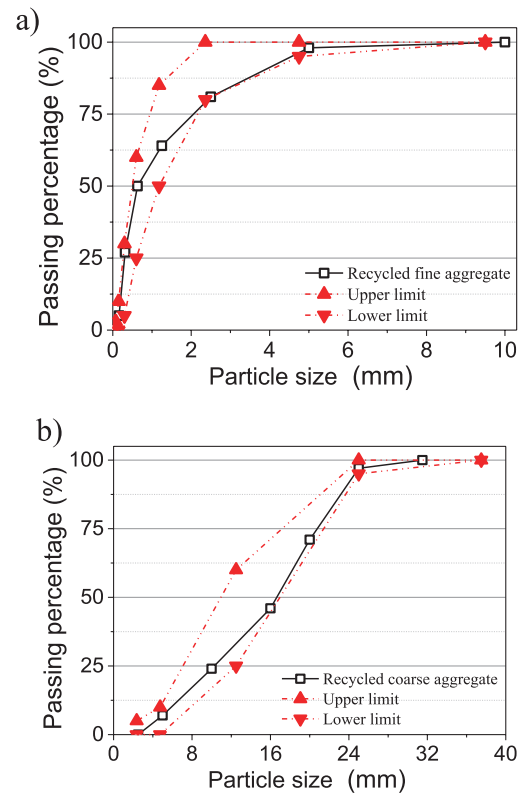
Fig. 1. Appearance of a) RFA and b) RCA.

Fig. 2. Particle size grading of recycled aggregates: a) RFA, b) RCA.

sand and crushed stone (or gravel) for ordinary concrete [35], the main physical and mechanical properties of recycled aggregates are provided in Table 1. The particle size distributions of recycled fine aggregates (RFA) and recycled coarse aggregates (RCA) are shown in Fig. 2 and compared with the limits from the standard specification for concrete aggregates ASTM C33:2016. The comparison shows that all the aggregates satisfy the recommended grading limits.

Additives

Two additives were used to ensure the workability of the concrete mix containing demolished waste. The first one is an expansive agent (EXP). It creates volumetric expansion which is considered very effective in reducing the crack potentials and improving the durability of the concrete mix. The EXP is mainly composed of CaO, Al_2O_3 and SO_3 (in total of 94.15%), as well as a small quantity of Fe_2O_3, MgO, K_2O, Na_2O, and SiO_2 (in total of 4.75%). The details about the chemical compositions of EXP are listed in Table 2. The second additive is a type of polypropylene

Table 1. Physical and mechanical characteristics of recycled aggregates.

Properties	Fine aggregate		Coarse aggregate	
	RFA	ASTM C33 limit	RCA	ASTM C33 limit
Apparent density (kg/m³)	2620	-	2630	-
Bulk density (kg/m³)	1530	-	1520	1200-1750
Water adsorption (%)	1.73	0-4%	1.14	0-4%
Specific gravity	2.45	2.4-2.9	2.61	2.4-2.9
Crushing value index (%)	-	-	24.6	-
Clay lumps (%)	0.1	≤3.0	0.1	≤5.0
Silt content (%)	1.5	≤5.0	0.4	-

Table 2. Chemical compositions of Portland cement, fly ash and expansive agent.

Compositions (%)	Portland cement	Fly ash	Expansive agent
SiO_2	23.15	53.97	1.24
Fe_2O_3	2.88	4.16	0.67
CaO	58.44	4.01	54.38
Al_2O_3	6.15	31.15	12.61
MgO	2.32	1.01	2.06
SO_3	2.26	0.73	27.16
TiO_2	-	1.13	-
K_2O	0.61	2.04	0.63
Na_2O	-	0.89	0.15
P_2O_5	-	0.67	-
NiO	-	0.11	-
Loss on ignition	4.19	0.13	1.1

fiber (PPF). It was obtained from a local fiber supplier, and used to enhance the mechanical properties of cementitious composites. According to the supplier, the key properties of PPF such as physical and mechanical parameters are shown in Table 3.

Cement, Fly Ash and Water

Portland cement (P.O. 42.5) and fly ash were used as binder paste. Cement was purchased from a local cement manufacturer. Fly ash originated from the coal combustion processes, which was obtained at a local thermal-electric power plant. Table 2 provides the chemical compositions of the cement and fly ash. Tap water was used as mixing water without any chemical compounds.

Mechanical Test Method

Sample Preparation

Mix design for the concrete mixtures used in the study is depicted in Table 4. All aggregates were oven-dried before mixing. Solid ingredients were added together and mixed for about 2 minutes. Water and EXP were then added and mixed uniformly. For fiber-reinforced samples, fibers were added manually and mixed for another 3 minutes. Finally, the fresh concrete mixture was cast into lubricated cubic molds and then compacted using a poker vibrator. After compaction the samples were left undisturbed for 24 h before being demolded. All concrete specimen were cured in a standard curing chamber for 7 and 28 days at 20 ± 3ºC with a relative humidity of 90 ± 5% in order to evaluate compressive strength of the concrete. The polypropylene fibers for all reinforced mixtures was dosed at 0.4% by weight of mix according to relevant research, and the EXP was dosed at 6%, 9%, 12% by weight of the cementitious material, as listed in Table 4. Besides that, to determine the effect of additives on the RAC, conventional concrete (CC) with natural aggregate was considered from literature. In order to ensure the accuracy of the test, three parallel samples were made for each group.

Test Procedure

The compressive property of concrete cubes ($150 \times 150 \times 150$ mm) was tested according to local standard GB/T 50081 using a UTM5105 electronic universal testing machine. A uniform loading rate at 0.15 mm/min was implemented in compression. Three replicates were reported for each mix. The compressive strength is calculated as follows:

$$f_{m,cu} = K \frac{N_u}{A}$$

(1)

where $f_{m,cu}$ is the compressive strength (MPa). N_u is the damage pressure and K is the conversion factor, which is 1.35 in this test. A is the contact area (m^2).

Microstructure Test

Scanning electron microscopy (SEM) was then performed to study the microstructure characteristics under different mixture proportions. The concrete samples cured for 28 days were soaked in anhydrous ethanol and the hydration was stopped for 48 hours. The samples were then dried in an oven at 50ºC for 15 hours. After drying, the dried samples were crushed into 5×5 mm for microscopic examination.

Table 3. Physical and mechanical parameters of polypropylene filament fiber.

Length (mm)	Diameter (μm)	Density (g/cm³)	Tensile strength (MPa)	Elastic modulus (GPa)	Melting point (ºC)	Rupture elongation (%)	Picture
6	45	0.91	400	8.0	165	8.2	

Table 4. Mix design for 1 m³ concrete.

Concrete mixes ID	Water (kg)	Binder (kg)		Natural aggregate (kg)		Recycled aggregate (kg)		Additives (%)	
		Cement	Fly ash	NFA	NCA	RFA	RCA	EXP	PPF
CC	182	335	-	865	1075	-	-	-	-
RAC	160	290	69	-	-	737	1018	-	-
RAC-EXP6	160	290	69	-	-	737	1018	6%	-
RAC-EXP9	160	290	69	-	-	737	1018	9%	-
RAC-EXP12	160	290	69	-	-	737	1018	12%	-
RAC-PPF	160	290	69	-	-	737	1018	-	0.4%
RAC-EXP6-PPF	160	290	69	-	-	737	1018	6%	0.4%
RAC-EXP9-PPF	160	290	69	-	-	737	1018	9%	0.4%
RAC-EXP12-PPF	160	290	69	-	-	737	1018	12%	0.4%

CC: conventional concrete, the detail of the composition was obtained from Ali et al. [36]; NFA: Natural fine aggregate; NCA: Natural coarse aggregate.

Environmental Analysis

Leaching of Heavy Metals

Heavy metals are typical pollutants, which can be enriched in organisms and cause great damage to animal and human health. Construction waste contains a small amount of heavy metals. For safety reasons, the leaching of heavy metals was measured on the basis of the EA NEN 7371 [37], which is considered to be the most suitable method for evaluating the leaching of heavy metals in construction waste [38].

RCA and RFA were soaked in deionized water according to a certain solid-liquid ratio, and the pH value was adjusted to a predetermined value with hydrochloric acid. After soaking in the solution for 5 days, centrifuged at 4000 rpm for 30 minutes, and the supernatant was filtered. The concentration of heavy metals was determined by inductively coupled plasma mass spectrometry (ICP-MS) and the leaching amount of heavy metal ions was calculated.

Carbon Emission

The environmental impacts of all the different recycled concrete mixes were compared to each other, and also to the conventional concrete mix (CC). The main aim was to assess the potential environmental benefits of RC. The carbon emissions of RC were estimated based on some of the mix proportions presented in Table 5.

The functional unit of assessment in this study was defined as one cubic meter of concrete to ensure the comparability between different types of mixtures. Note that one cubic meter of concrete was selected as the function unit as it is more representative than one kilogram [39].

The inventory analysis is considered as a detailed compilation of all the material and energy inputs and outputs in the life cycle phases [40]. Most of the data about the materials and energy were collected from various sources, e.g. from extensive interviews with the local concrete production sector and recycling plants, from the available literature, etc.. The carbon emission per unit volume of concrete was calculated from emissions associated with its raw materials as given in Table 5. No official data for carbon emission of recycled aggregates is available. Therefore, the data related to production of CC and RA were calculated from energy consumption during various recycling activities as listed in Table 6.

Table 5. Carbon emission factor of raw materials per kilogram production.

Material	Carbon emissions (CO_2)	References
Portland cement	0.83 kg/kg	[41]
NFA	0.0050 kg/kg	[42]
NCA	0.0062 kg/kg	[42]
Fly ash	0.009 kg/kg	[43]
Water	0.0003 kg/kg	[41]
PPF	1.85 kg/kg	[44]
EXP	0.000181 kg/kg	Calculated[1]
Diesel	2.764 kg/kg	[45]
Electricity	0.9746 kg/kWh	[45]

[1] Calculated, calculated by the authors.

Table 6. Energy consumption during the production of recycled aggregates.

Materials	Activity	Energy requirements	References
RFA	Crushing, sieving, on-site transport and handling	3.06 kWh/t (electricity) & 0.42 kg/t (diesel)	Calculated [1]
RA	Crushing, sieving, on-site transport and handling	1.11 kWh/t (electricity) & 0.42 kg/t (diesel)	Calculated [1]

[1] Calculated, calculated by the authors.

Results and Discussion

Compressive Strength

The compressive strength and deformation of non-reinforced concrete mixtures with different expansive agent contents were determined after 7- and 28-day curing, and the results are presented in Figs 3 and 4. As shown in Fig. 3a), the highest compressive strength was achieved by the concrete mixture with no expansive agent. For the three concrete mixtures with EXP, the addition of different dosages of EXP results in a degradation in the compressive strengths at early age compared to the control mixture. It can be seen from Fig. 3a) that it is equal to approximately 19.7%, 5.19% and 18.14% of strength loss for the concrete mixtures with 6%, 9% and 12% EXP, respectively. The strength loss of the EXP-based concrete mixtures

may be induced by the lower total content of both water and cement compared with the mixture with 0% EXP. Therefore, the early hydration kinetics might be influenced by the hydration reaction rate of cement, resulting in a drop in the early-age strength [46].

In Fig. 3, the compressive strength increases gradually with curing time. The compressive strength after 7-day curing is approximately 57.3 - 86.1% of the corresponding values after 28-day curing. Fig. 3b) illustrates the strength after 28 days of curing. The RAC without EXP has relatively lower compressive strength than mix containing EXP. It is observed that the compressive strength of RAC without expansive agent is 20.8%, 10.9% and 10.1% lower than that of RAC with 6%, 9% and 12% expansive agent contents, respectively. This is because the addition of a certain amount of EXP induces the formation of a hydration product - ettringite crystals, which fills the gap of the cementitious matrix and further densifies the microstructure, and therefore increases the compressive strength. Additionally, the specimen with 9% EXP exhibits better mechanical performance relative to other specimens. As presented in Fig. 3b), it seems that the concrete mix with 6% EXP not only had higher strength, but also shows higher deformation tolerance indicating higher cracking resistance. The presence of EXP shows a positive effect on the mechanical properties of RAC.

It is also found, however, that the compressive strength increases and subsequently decreases with increasing EXP content after 28-day curing. This is because a high EXP content in RAC could result in an excessive expansion pressure, which causes the microcracks and is harmful to the pore structure [47]. The concrete mixes after 28-day curing are compared through microscopic observation as shown in Fig. 4, and a large quantity of pores and microcracks exist in the concrete mixtures with different expansive agent contents. The hydration reaction of EXP generates ettringite crystals which can fill the hole, and significantly increase the compactness of the concrete material. The higher amount of EXP causes more ettringite crystals as seen from Fig. 4. A denser concrete typically indicates better fracture resistance. The excessive expansion causes new microcracks in the internal structure, which also explains that a high EXP content could be detrimental to the development of compressive strength.

Fig. 5 shows the combined effect of EXP and polypropylene fiber on the compressive strength and deformation of the RAC concrete mixtures. Compared
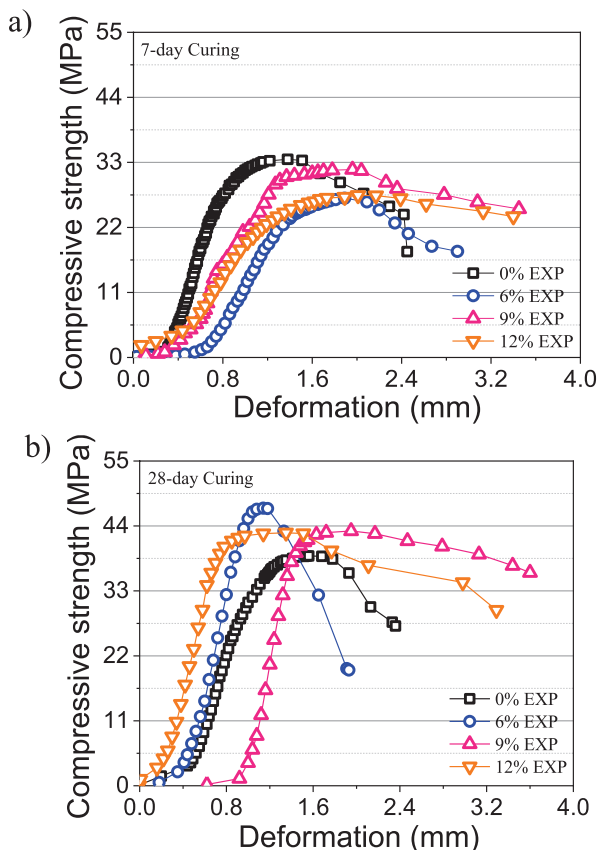

Fig. 3. Stress-strain relation of the concrete mixture, after a) 7 and b) 28 days curing (without fiber).
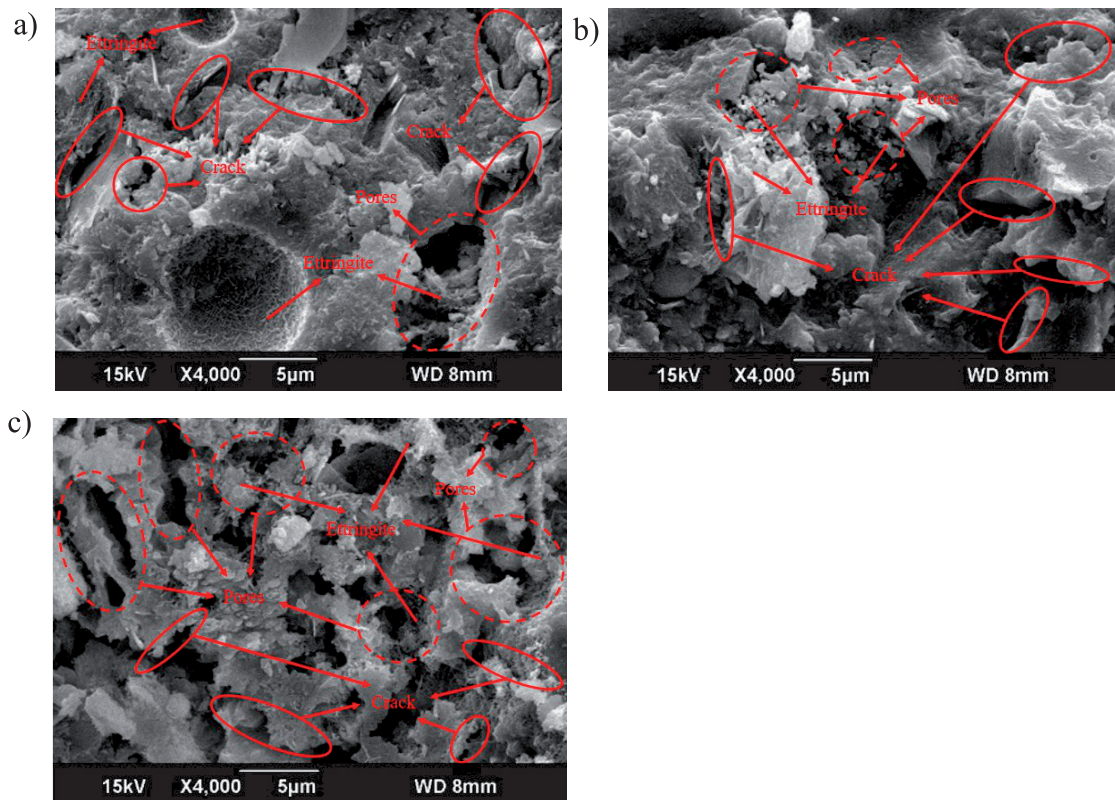
Fig. 4. SEM image of concrete cubes at different EXP dosage: a) 6% EX, b) 9% EXP, c) 12% EXP.

with Fig. 3 and Fig. 5, in the case of 28-day curing, the maximum compressive strength of fiber-reinforced specimens containing 0%, 9% and 12% EXP are 39.3 MPa, 44.4 MPa and 41.9 MPa respectively, which are 1.0%, 2.7% and 0.1% higher than those of the unreinforced specimens, except for the specimens with 6% EXP. Fiber can strongly bond the cement paste and aggregates providing a higher strength for concrete [48]. As shown in Fig. 3 and Fig. 5, the curves of concrete mixtures with and without fiber show different behaviors. The strength-deformation response of unreinforced specimens containing 0% and 6% EXP demonstrate brittle feature that the post-peak part of the curve is relatively sharp. However, the strength-deformation response of fiber-reinforced specimens presents some ductility, represented by a flatter post-peak curve. The ultimate deformation of reinforced RAC is higher than that of unreinforced RAC. As presented in Fig. 5, the ultimate deformations of reinforced specimens are 1.7 mm (0% EXP), 1.3 mm (6% EXP), 1.8 mm (9% EXP) and 1.8 mm (12% EXP), respectively, which increases by 5.9% - 22.2% compared to unreinforced specimens, demonstrating that the addition of fiber enhances the ultimate deformation tolerance of concrete specimens. In addition, the effect of EXP content on the compressive strength of fiber-reinforced specimens is relatively small. The difference of compressive strength among all specimens is not significant, while 9% EXP content is the optimal content yielding the highest strength.
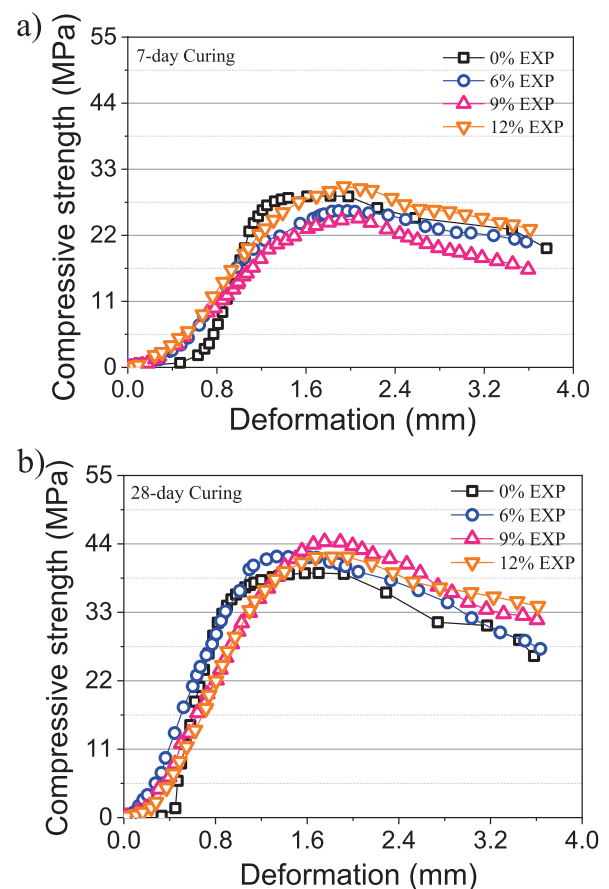

Fig. 5. Stress–strain relation of the concrete mixture, after a) 7 and b) 28 days curing (with fiber).

Environmental Impact Analysis

Leaching of Heavy Metals

In fact, construction waste usually contains pollutants including heavy metals, which may cause negetive effects on the surrounding environment [49-51]. Thus, potential environmental risks after using such recycled materials should not be overlooked, in particular, considering the increase of specific surface area after crushing and the differences of RA. The leaching assessment of heavy metals was therefore carried out. After the pre-experiment, the leaching of heavy metals could not be detected at pH 7. When the pH was 3, only Zn, Cu and Cd could be detected in extremely small amount which is very close to the minimum detection capability. Therefore, pH was adjusted to 1 with hydrochloric acid. It should be noted that the pH value of rainwater is only about 5.6, and it is difficult to reach 1 in the natural environment. Therefore, the heavy metal leaching of recycled aggregate under extreme conditions is considered in this paper.

The leaching results of RCA and RFA are shown in Fig. 6. With the increase of liquid-solid ratio, the leaching mass of heavy metals increased significantly. No matter RFA or RCA, the heavy metal with the largest leaching amount is Zn, followed by Cu, Cd, Pb and Ni. Compared with RCA, RFA has a greater leaching amount of heavy metals. This is because the particle radius of RFA is smaller, so its specific surface area is larger which promotes the leaching of heavy metals. The applicability of construction waste in environmental issues can be estimated based on its leaching behavior. Some European countries regulate recycled materials by establishing limit values concerning leachability of pollutants, which is essential to determine their potential uses [52, 24]. Table 7 summarized limit values for filling materials in Germany, Austria and Switzerland, and compared them with the leaching results of construction waste in this study (leaching results in L/S = 20 are selected because the leaching amount is the most in this state). The main results show that both RFA and RCA can well meet the requirements for insert material in Switzerland, but for the standards of Germany and Austria, the leaching mass of Zn and Cd in this construction waste are slightly higher. However, Ferreira et al. argued that if concrete is used in internal structures, the application of waste as lightweight aggregates is not expected to cause environmental issues since the leaching behavior of heavy metal is not significant [53].
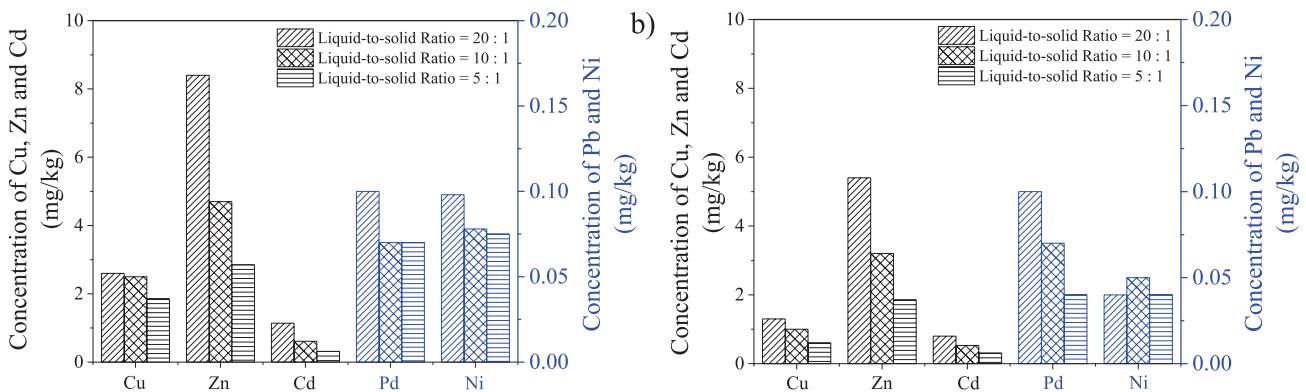

Fig. 6. Leaching amount of heavy metals of a) RA, b) RCA.

Table 7. Leaching results of construction waste compared to limit values for filling materials in some European countries. (The leaching results are in L/S = 20).

Class	Germany	Austria	Switzerland	Leaching results for RFA in L/S = 20	Leaching results for RCA in L/S = 20
	Class I Inert	Class A Inert	Inert		
Unit	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Cu	10	2	2	2.6	1.3
Zn	5	10	10	8.4	5.4
Cd	0.5	0.05	20	1.14	0.8
Pd	2	1	100	0.1	0.1
Ni	2	1	2	0.1	0.04

Carbon Emission

Carbon emission for each concrete mix is summarized in Table 8. Calculations were made from the following equation:

$$TC = \sum MC_i + \sum EC_j \qquad (2)$$

where TC is the total carbon emission during the production of concrete (kg-CO_2), MC_i is the carbon emission of the *i*th raw material during its production (kg-CO_2), and EC_j is the carbon emission of the *j*th energy consumed to undertake a particular activity (kg-CO_2).

$$MC_i = MQ_i \times CEF(M)_i \qquad (3)$$

where MQ_i is the consumption of the *i*th material (kg), and $CEF(M)_i$ is the emission factor for the *i*th material (kg-CO_2/kg) as listed in Table 5.

The carbon emission of the jth energy was calculated using Eq. (4):

$$EC_j = EQ_j \times CEF(E)_j \qquad (4)$$

where EQ_j is the consumption of the *j*th energy (kg, kW), and $CEF(E)_j$ is the emission factor for the *j*th energy (kg-CO_2/kg, kg-CO_2/kWh) as listed in Table 6.

Fig. 7 shows the relative contribution of different compositions to total carbon emissions in concrete mixtures. As shown, for both natural aggregate concrete and recycled aggregate concrete, the cement production generates the majority of the total carbon emissions, by accounting for 96.18%, 97.82%, 97.82%, 91.57% and 91.49% of the total emissions of CC, RAC, RAC-EXP9, RAC-PPF and RAC-EXP9-PPF, respectively. This is mainly caused by the calcination of clinker and the fossil fuel usage. Portland cement contains clinker of more than 90% by weight, which is produced by limestone combustion. It is estimated that 0.5 tons of CO_2 is released for every ton of CaO produced.

The lower carbon emission of recycled concrete product compared to that of conventional concrete is related to the incorporation of low-carbon binder - fly ash, accompanied by a decrease in the mass of cement used [54]. Fly ash is considered as a by-product in waste incineration, and therefore is described as 'zero emission material' [55]. In order to quantify the environmental impact of concrete containing fly ash, transportation process of fly ash should be considered as an important aspect [56]. Therefore, the corresponding energy and emissions are not negligible. The final emission factor that was used for fly ash in this study is 0.009 CO_2-kg/kg (Table 5), which considers the production process of concrete.

Carbon emission decreases considerably with the replacement of natural aggregate by recycled aggregate. For example, RAC mixture shows 42.39 kg-CO_2/m³ lower emission than CC mixture as listed in Table 8. These two types of aggregates emit 11.0 and 5.3 kg-CO_2/m³, respectively. Furthermore, the influence of natural aggregates and recycled aggregates on the emission contribution has been compared in Fig. 7, and recycled aggregates have a lower contribution than virgin aggregates to the total emissions.

As shown in Table 8, the primary source of CO_2 emissions in natural aggregate is coarse aggregates. Based on the emission factors in Table 5, production of a kilogram of NFA generates 80.6% of the emissions compared with NCA. Flower and Sanjayan attributed the difference of the emissions between fine and coarse aggregates to the crushing process. In other words, NFA emits less CO_2 since they are not crushed [33].

Regarding recycled aggregates, however, RFA creates the most of total CO_2 emissions during the production of recycled aggregates, as shown in Table 8. Fig. 8 illustrates the contribution of diesel and electricity to the CO_2 emissions. As can be seen that the primary contribution in RFA production is from electricity, which is approximately about 71.9%. While the diesel has relatively high emission factors per kilogram production, it contributes less than 30% in RFA production as only small quantity is used. Using
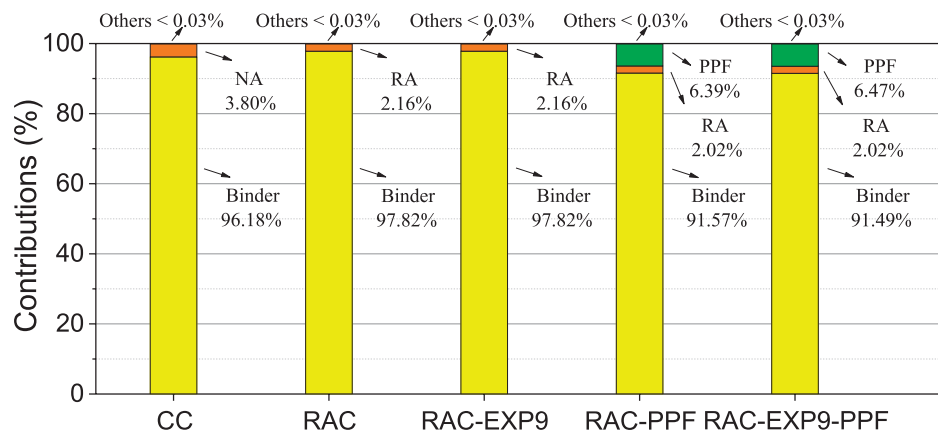

Fig. 7. Carbon emission contributions of different materials.

Table 8. Carbon emissions for different types of concretes studied in LCA (kg-CO_2/m³).

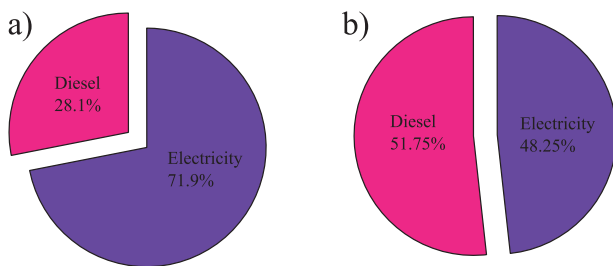| Concrete mixes ID	Binder		Natural aggregate		Recycled aggregate		Others		Fiber	Total
	Cement	Fly ash	NFA	NCA	RFA	RCA	Water	EXP		
CC	278.05	/	4.325	6.665	/	/	0.055	/	/	289.095
RAC	240.7	0.621	/	/	3.053	2.283	0.048	/	/	246.705
RAC-EXP9	240.7	0.621	/	/	3.053	2.283	0.048	0.0058	/	246.711
RAC-PPF	240.7	0.621	/	/	3.053	2.283	0.048	/	16.828	263.533
RAC- EXP9-PPF	240.7	0.621	/	/	3.053	2.283	0.048	0.0058	17.067	263.778

Fig. 8. Carbon emission contribution of each energy source associated with RA.

the energy consumption numbers presented in Table 6, CO_2 emissions per ton of RA using electricity and diesel were calculated to be 1.08 CO_2-kg and 1.16 CO_2-kg, respectively. Similarly, as shown in Fig. 8, it can be noticed that diesel and electricity contributed almost equally during RA production.

In this study, PPF and EXP were considered as admixtures to enhance the engineering properties of concrete. In Table 8, analysis of total emissions studied in LCA shows that PPF can significantly increase the carbon emission. The increase is mainly attributed to the high emission of PPF. In Table 5, the emissions of PPF production are 122.89% higher than that of the cement production. For EXP, the manufacturer supplied the carbon emission factor as presented in Table 5. The emissions value associated with the production of expansive agent is found to be minimal. The emission of EXP in the two concrete mixes with EXP as listed in Table 8 is 0.0058 kg-CO_2 per cubic meter. Hence, the emission contributions due to expansive agent is found to be negligible.

Conclusions

In this study, concrete mix using recycled aggregates and different additives were evaluated as regard their mechanical properties and environmental impact. Through the results of this study, it could be concluded as follows:

(1) The addition of expansive agent has a positive effect on the mechanical properties of recycled concrete mixes. The maximum compressive strength of concrete mixtures with expansive agent is 10.1% - 20.8% higher than that without expansive agent. SEM observations showed that the hydration reaction of EXP generates ettringite crystals which grow alternately in the holes to form a network structure and significantly increase the compactness of the concrete. However, when the EXP content reaches 12%, the excessive expansion pressure causes microcracks in the internal structure and is detrimental to the compressive strength.

(2) The benefit of fiber reinforcement was noticed on the compressive strength and deformation tolerance of the concrete mixes. Fiber-reinforced concrete mixes show ultimate deformation of 5.9% to 22.2% higher than unreinforced concrete.

(3) When the pH is equal to 1, the leaching amount of heavy metals can meet the standard requirements, and the maximum leaching amount is only 11.67% of the required value.

(3) The LCA results show that the emission out of cement production accounts for more than 90% of the total emission for all concrete mixes made of natural concrete or recycled concrete due to the large amount of carbon emission generated during the calcination process through the clinker production and the usage of fossil fuel. Carbon emission decreases slightly with the replacement of natural aggregate by recycled aggregate. Part of this reduction is due to the lower carbon emission of recycled aggregates compared to that of the natural aggregates.

Conflict of Interest

The authors declare no conflict of interest.

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