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RESEARCH ARTICLE

Vivian W. Y. TAM, Khoa N. LE, Ana Catarina Jorge EVANGELISTA, Anthony BUTERA, Cuong N. N. TRAN, Ashraf TEARA

Effect of fly ash and slag on concrete: Properties and emission analyses

Abstract Recycled concrete is a material with the potential to create a sustainable construction industry. However, recycled concrete presents heterogeneous properties, thereby reducing its applications for some structural purposes and enhancing its application in pavements. This paper provides an insight into a solution in the deformation control for recycled concrete by adding supplementary cementitious materials fly ash and blast furnace slag. Results of this study indicated that the 50% fly ash replacement of Portland cement increased the rupture modulus of the recycled concrete. Conversely, a mixture with over 50% cement replacement by either fly ash or slag or a combination of both exhibited detrimental effect on the compressive strength, rupture modulus, and drying shrinkage. The combined analysis of environmental impacts and mechanical properties of recycled concrete demonstrated the possibility of optimizing the selection of recycled concrete because the best scenario in this study was obtained with the concrete mixture M8 (50% of fly ash + 100% recycled coarse aggregate).

Keywords recycled aggregate, recycled concrete, fly ash and slag

1 Introduction

The process of recycling is of substantial importance to the longevity and quality of life for current and future generations of humans. Recycling has shown substantial progress in different aspects of life, including environmental, social, and economic aspects. Decades ago, recycling only involved paper, cardboard, oil, metal, and plastic processing. However, the scope of recycling has become wider and more inclusive at present than the past. A field of recycling that exhibits a surplus of potential is concrete recycling (Tam et al., 2014; Zhang et al., 2015).

At the end of the World War 2, recycled aggregate started to be used in many countries in reconstructing infrastructures, especially in roads that were damaged during the war. Concrete has been successfully recycled in several countries, including the Netherlands, Canada, Germany, Japan, South Africa, UK, Russia, and France. The use of recycled aggregate has, without a doubt, many positive aspects, involving the reduction of finite raw material usage, thereby minimizing energy consumption. Consequently, construction cost is decreased, thereby improving sustainability. A large number of construction and demolition wastes, approximately 30%–40%, have been increasing the landfill disposals and cost. As a consequence, it has been leading the construction industry to replace natural aggregate by recycled aggregate. Recycled aggregate can be derived from many different construction and demolition waste types, especially demolished concrete, clay brick, and ceramic. All these materials can be used in concrete preparation and can show considerable results (Olorunsogo and Padayachee, 2002; Kong et al., 2010).

Concrete recycling has evolved quickly over the years to solve several problems generated by concrete wastes. Demolished concrete recycling is highly beneficial, especially in areas where dumping cost is exceedingly high (Mater et al., 2004). The number of disposal sites worldwide and the allowable waste volume to be disposed have also decreased. The governments of UK and other countries have introduced landfill taxes supporting environmental concerns. Thus, construction industry ensures easy and cheap process to recycle demolition debris

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Vivian W. Y. TAM (✉)
College of Civil Engineering, Shenzhen University, Shenzhen 518061, China
E-mail: vivianwytam@gmail.com

Khoa N. LE, Ana Catarina Jorge EVANGELISTA, Anthony BUTERA, Cuong N. N. TRAN, Ashraf TEARA
Western Sydney University, School of Computing, Engineering and Mathematics, Locked Bag 1797, Penrith, NSW 2751, Australia

because the mechanism is appropriate environmentally and economically. A similar problem was also discussed and revealed that the decisions made by the Hong Kong Government decrease the disposal places for demolition waste (Tam et al., 2005).

The utilization of recycled aggregate can reduce natural aggregate consumption, thereby saving natural resources. Landfill space can also be minimized by the reuse of recycled aggregate in concrete mixtures instead of being placed in landfills. Considering the significant availability of construction and demolition waste, recycled aggregate can present economic benefits compared with natural aggregate (Poon and Chan, 2007; Kou et al., 2014).

To present differences between recycled and natural concretes, researchers conducted experiments using recycled and natural aggregates for concrete production (Xiao et al., 2005). The prism specimens of both concrete types were used. Each prism was compressed three times. Each compression, compression loading was higher than that of the previous test on the same prism. The final results with respect to the natural concrete showed that cracks are absent in the first loading stage. The second loading stage produced some small vertical cracks. In the last loading stage, with high compression, microcracks become macrocracks. However, the recycled concrete indicated that the first two stages are approximately the same, thereby producing microcracks. However, in the last stage, the microcracks develop rapidly to inclined macrocracks, and the specimen was easily broken into tiny fragments.

Recycled aggregate is heterogeneous, more porous, and less dense than natural aggregate. Consequently, recycled aggregate is only used in low-grade purposes, especially as road base (Ryu, 2002; Levy and Helene, 2004; Etxeberria et al., 2007). As a result of poor recycled aggregate quality, new supplementary concrete pouring techniques must be utilized to bridge the performance gap between recycled and natural concretes (Sim and Park, 2011). Therefore, additional studies are needed to improve the recycled aggregate properties. Many different processes and techniques, including ultrasonic cleaning method for the removal of loose particles, ball milling for the separation of the attached old mortars, the addition of high-quality granular material, blending with hydrated lime and fly ash, and heating and rubbing methods, have been used and developed (Kong et al., 2010).

Carefully designed mixing approaches can improve the physical and mechanical performances of recycled concrete. Procedures and ingredients of a new successful mixing approach named the two-stage mixing approach were developed (Tam et al., 2007). The double- and triple-mixing methods in enhancing the interfacial transition zone (ITZ) were also developed (Kong et al., 2010). All of these methods improved the ITZ, thereby improving the recycled concrete performance.

In addition to recycled aggregate, fly ash and slag are commonly used to replace cement for concrete production. Fly ash is manufactured from the burning coal powder from power stations for electricity or any burning coal powder. Fly ash is a by-product of burning coal that is present in exhaust gases. Chemically, fly ash contains SO_3, Al_2O_3, SiO_2, TiO_2, Fe_2O_3, MgO, CaO, and Na_2O. Among these compounds, the largest percentages of the elements that form fly ash are observed in SiO_2 and Al_2O_3 that together make up approximately 45%–80% of ash (Cetin et al., 2012; Qiu et al., 2014). Table 1 shows the chemical analysis of the ingredients of fly ash (Kaur et al., 2012). As an engineering material, fly ash can be used for many different purposes, including as replacement for Portland cement in concrete and as a soil improvement agent. Fly ash is also considered as flowable fill and structural fills/embankments, asphalt pavements, and grouts for pavements subsealing (Kaur et al., 2012). At least one of several objectives and benefits can be achieved using fly ash in cement. Fly ash reduces the concrete cost by reducing the cement content. Fly ash is also an effective admixture in improving concrete workability. Fly ash also decreases the heat of hydration, mainly in mass concrete, and in attaining the required levels of strength in concrete at ages beyond 56 days (Kaur et al., 2012). Fly ash also improves concrete durability. The use of fly ash also decreases the amount of cement. Consequently, cement production can be reduced, and energy can be used; therefore, greenhouse gases and other environmentally harmful gases are reduced (Kaur et al., 2012).

Table 1 Chemical analysis of fly ash (Kaur et al., 2012)

Parameter	Percentage (%)
SiO_2	45.0–64.4
CaO	0.7–7.5
Al_2O_3	19.6–30.1
Fe_2O_3	3.8–23.9
Na_2O	0.3–2.8
MgO	0.7–1.7
KO_2	0.7–2.9
Loss on ignition	0.4–7.2

Slag is derived from blast furnaces used in iron production. Blast furnaces are formed after a reaction including a mixture of iron ore, coke, and limestone which are melted and mixed with each other at a temperature of 1500°C. This same reaction produces two other elements, as follows: the first one is the molten iron, and the other is the molten slag that floats on top of molten iron because of its low weight. Silicates and alumina, which are derived from iron ore, are the main ingredients of molten slag. Slag from granulated and small particles (granular) is formed by cooling the molten slag by using high-pressure water jets. The granular particles contain approximately 95% non-crystalline Ca alumina silicates. After drying and grinding the granules, particles were transformed to slag in a form of extremely fine powder. The essential ingredients of slag cement include silicates and Ca alumina silicates. Slag is not a metallic material, but it is mainly produced by glassy and crystalline phases; the first one is the cause of cementation properties. Glass represents approximately 85%–90% of the total weight in slag cement. Finally, slag has the essential chemical components, especially, CaO, SiO_2, Al_2O_3, and MgO, which are the same as the ordinary Portland cement but in different percentages (Kaur et al., 2012). Slag has several different benefits when it is partially used to replace cement. Slag is also environmentally useful because it reduces energy consumption; consequently, it decreases the greenhouse gas emissions and conserves natural resources (Kaur et al., 2012). The importance of using slag in cement lies in its significant roles. Slag improves workability, compaction characteristics, and durability. Slag also increases strength and pump ability. The use of slag also decreases permeability and contributes high resistance to all chloride penetration and sulfate attacks. Slag also enhances the surface finish and the architectural appearance in addition to the life cycle of concrete structures. Finally, slag decreases the maintenance and repair costs and suppresses efflorescence (Kaur et al., 2012).

The use of recycled aggregate, fly ash, and slag decreases the environmental impact. However, these materials were previously considered of lower quality than traditional concrete. Increasing the amount of used fly ash improves the mechanical performance (Kou et al., 2008; Padmini et al., 2008). However, upon the addition of recycled aggregate replacement ratios of > 50%, fly ash cannot contribute to the increase in recycled concrete performance compared with natural concrete in terms of compressive strength, tensile strength, or static modulus of elasticity. The compressive strength of concrete is affected by many factors, which mainly include the quantity and quality of recycled aggregate used, water-to-cement ratios, water-to-binder ratios, and ITZ between the aggregate and cement paste. The compressive strength of concrete is also based on the mixing method and mineral additions, especially the addition of fly ash and slag (Hansen, 1992; Berndt, 2009; Kou et al., 2011; Kou et al., 2012).

Several researches (Hemalatha and Ramaswamy, 2017; Yu et al., 2017) investigated the use of high fly ash volume as a partial cement replacement in concrete production. The main concern is whether or not cement can be replaced by the fly ash with the limiting quantity of above 15%–20% by mass in the concrete (Berndt, 2009).

This study emphasizes high-volume fly ash (UVFA) and slag concrete, which was defined by some authors (Kurad et al., 2017; Yu et al., 2017) as the concrete with fly ash that replaces > 50% of the cement. This research aims to (1) replace cement in decreasing greenhouse gas emission by slag (0% and 50%) and fly ash (0% and 50%) from cement for concrete production, (2) replace natural aggregate with recycled aggregate (0%, 50%, and 100%) in decreasing construction and demolition waste disposals in landfills, and (3) combine the analyses of environmental impacts and mechanical properties of the recycled concrete.

The International Organization for Standardization (ISO) has produced a series of standards for life cycle assessment focusing on the technical and organizational aspects of a life cycle assessment project.

On the basis of a case study of pile foundation construction, Australian researches (Sandanayake et al., 2016) reported the relevance of construction material as a pollutant product, thereby showing that embodied emissions from material are responsible for 77.1% of the total greenhouse gas emissions in the foundation construction, whereas emissions from equipment usage and transportation account for 13.5% and 9.4%, respectively. Among the negative impact caused by the production and its use of construction material, the concern for the national waste generation (Tam, 2009) revealed that approximately 32.4 million tons of solid waste are generated in Australia annually, of which approximately 42% accounts for the construction and demolition sectors.

In 2015, the presented Life Cycle Inventory of Cement and Concrete produced in Australia (Sharma and Grant, 2015) considered three concrete types (i.e., Ordinary Portland Cement Concrete, Concrete 30% ground-granulated blast-furnace slag, and Concrete 30% fly ash) by using natural aggregate (fine and coarse), admixtures, and water. However, the recycled aggregate was only present in an individual analysis on the basis of energy usage data published in Sustainable Aggregates CO_2 emission factor study commissioned by the Zero Waste South Australia (RMCG, 2010). Given the lack of research considering both the environmental impact of recycled aggregate and national data of the sustainability in the production of recycled concrete, this study aims to minimize the scarcity of suitable data in Australia.

The Australian National Life Cycle Inventory Database (2017) revealed that LCA methods and characterization factors underlying the impact assessment commonly reflect the environmental conditions of the region in which they were developed and may not always translate accurately to all regions. This finding indicated that life cycle assessment in Australia can result in uncertainty when the characterization factors developed in the European context (for example) are applied to the processes occurring in Australia (Alcas, 2017).

Currently, a specific carbon footprint standard ISO14067 describing the methodology to quantify the life-cycle on the basis of greenhouse gas emissions (e.g., carbon) of products established on LCA methodology, has been published. ISO 14067/2018 (2018) provides globally agreed principles, requirements, and guidelines on the quantification and reporting of the carbon footprint of a product. Life-cycle greenhouse gas emissions (LGE) involves the calculations of the global warming potential of the electrical energy sources through the life-cycle assessment of each energy source. In addition, life-cycle greenhouse gas emissions provides a systems perspective that evaluates GHG emissions from raw material extraction, processing, manufacturing, and transportation through the disposal of a product, material, or service (EPA, 2016; Kumanayake and Luo, 2018; Le et al., 2018). Kumanayake and Luo (2018) also reported that the carbon emissions at the material production stage accounts for 32% of the total carbon emissions of the building life cycle.

According to Chau et al. (2015), the life cycle assessment, life-cycle energy consumption, and LGE assessments form three streams of life-cycle studies. According to the Green Star Environmental Rating System, the material category accounts for 14% of credit points, which can be achieved from 8 major categories (Le et al., 2018). The LGE from concrete production increases according to the cement content used in the concrete mix. The GHG emissions are related to the Portland cement clinker production. In general, Portland cement composition are as follows: 5% of gypsum, 12% of supplementary cementitious material (SCM), including fly ash (or pulverized fuel ash), superfine fly ash, ground-granulated blast furnace slag, rice husk ash, natural pozzolans, colloidal silica, metakaolin, superfine calcium carbonate (pure limestone), and 83% Portland clinker (Metha and Monteiro, 2005).

The substitution of the limestone-based clinker by ground blast furnace slag (a by-product from the iron or steel industry), fly ash, and natural volcanic material is one feasible solution to reduce the volume of limestone-based clinker used in cement and GHG emissions associated with clinker production (Wang et al., 2013).

2 Materials and methods

2.1 Material

The materials used in this project are Portland cement, fly ash, slag, sand, natural aggregate (10 and 20 mm), and recycled aggregate (10 and 20 mm). The Portland cement used in this project was produced by the Cement Australia Pty., Ltd. The main components of the Portland cement are as follows (Cement Australia, 2016): Portland cement clinker ($<$ 97%); (2) gypsum, $CaSO_4 \cdot 2H_2O$ (2%–5%); (3) limestone, $CaCO_3$ (0%–7.5%); (4) CaO (0%–3%); (5) crystalline silica (quartz, $<$ 1%); and (6) hexavalent chrome, CrVI ($<$ 20 ppm).

Fly ash is widely marketed in Australia and a natural and industrial mineral with different natural advantages. As a raw material, fly ash is characterized as pozzolanic attributes. Fly ash also does not have any effect on the chemical composition of a concrete mixture. The main components of the fly ash are (1) crystalline silica (quartz) (30%–95%), (2) mullite (5%–30%), and (3) hexavalent chromium (chrome VI, $<$ 1 ppm; (Cement Australia, 2016).

Slag is derived from iron and steel during their manufacturing processes. Slag is processed in a way that granulated and ground granulated blast furnace slags are produced. Slag is characterized by its latent hydraulic properties that improves the durability properties of concretes. The main components of the slag are as follows (Cement Australia, 2016): (1) granulated blast furnace slag (at least 90%); (2) gypsum, $CaSO_4 \cdot 2H_2O$ (2%–5%); (3) hexavalent chrome, CrVI ($<$ 1%); and (4) crystalline silica (quartz, $<$ 1%).

Natural and recycled aggregate samples are collected from a recycling plant centralized in south-eastern Australia. The properties of the aggregate samples can be observed in Table 2, as follows:

2.2 Concrete mixtures

In this study, the experimental program was conducted for fly ash and slag with the replacement percentages of 0%

Table 2 Natural and recycled aggregate properties

Source	Australian Standards	Natural aggregate	Recycled aggregate
Grading	AS 1141.11.1	Pass	Pass
Water absorption (%)	AS 1141.6.1	1.02 (10 mm), 0.42 (20 mm)	5.02 (10 mm), 5.63 (20 mm)
Particle density on oven-dried basis (t/m^3)	AS 1141.6.1	2.59 (10 mm), 2.47 (20 mm)	1.44 (10 mm), 1.30 (20 mm)
Particle density on saturated and surface-dried basis (t/m^3)	AS 1141.6.2	2.61 (10 mm), 2.48 (20 mm)	1.51 (10 mm), 1.37 (20 mm)
Apparent particle density (t/m^3)	AS 1141.4	2.66 (10 mm), 2.50 (20 mm)	1.55 (10 mm), 1.40 (20 mm)
Aggregate crushing value (%)	AS 1141.22	21	34
Contaminant (%)	AS 1289.4.1.1	0	2
Flakiness index	AS 1141.15	28.27 (10 mm), 22.52 (20 mm)	15.12 (10 mm), 9.78 (20 mm)
Misshapen particle (%)	AS 1141.14	3.02	0.88

and 50% and the recycled aggregate with replacement percentages of 0%, 50%, and 100%. In total, nine different concrete types were produced and compared, while the water-to-cement ratio was kept at 0.45 for all mixes. The details of the mix proportions used for the concrete experiment and experimental designs on different fly ash, slag, and recycled aggregate replacement percentages are shown in Table 3 and 4, respectively, as follows:

Each concrete mixture produced 12 100 mm × 200 mm concrete cylinders to obtain compressive strength at 7, 14, and 28 days and three 75 mm × 75 mm × 285 mm prisms to obtain drying shrinkage and rupture modulus at 28 days.

The mixing procedure conducted in this paper was based on the Australian standards (AS 1012.2, 2014). The concrete mixing was first charged with approximately half of natural and recycled aggregates, then with sand, cement, and finally with the remaining aggregate. Then, water was immediately added after starting the operation for 2 min. No superplastiser or additive was added to any concrete mix in the experiment to ensure that the actual results from the fly ash, slag, and recycled aggregate replacement percentages were recorded and analyzed.

The concrete samples were demolded after 24 h of mixing and immediately placed in a room with controlled environmental conditions at the temperature of 22±2°C and the relative humidity level of 70% × 2%.

The properties on concrete drying shrinkage was tested according to Australian standards (AS 1012.13, 2014). The samples were immersed in water for the first 28 days for curing and then dried for the drying shrinkage test. After 296 days, the drying shrinkage samples was rewet for another 118 days (until day 415). An average of three measured results of the concrete samples for drying shrinkage is reported in this paper.

The compressive strength was obtained at 7, 14, and 28 days, and the rupture modulus was tested at 28 days according to the Australian standards (AS 1012.9, 2014; AS 1012.17, 2014). The mean values of the results of all tests carried out for each concrete mix with the standard deviations are shown in Table 6. All the standard deviations were low, which justified the use of only three samples.

Table 4 Experimental design on different fly ash, slag, and recycled aggregate replacement percentages

Mixes	Fly ash replacement (%)	Slag replacement (%)	Recycled aggregate replacement (%)
M1 (0-0-0)	0	0	0
M2 (50-0-0)	50	0	0
M3 (0-50-00	0	50	0
M4 (0-0-50)	0	0	50
M5 (50-0-50)	50	0	50
M6 (0-50-50)	0	50	50
M7 (0-0-100)	0	0	100
M8 (50-0-1000	50	0	100
M9 (0-50-100)	0	50	100

2.3 Environmental impact analysis by the LGE model

To evaluate the environmental impact of recycled concrete, this study adopted the LGE model created by Le et al. (2018). The model incorporates different aspects of concrete mixing, including the variations of concrete strength (from 20 MPa to 100 MPa), aggregate type, SCM (fly ash, blast furnace slag, and silica fume), and exposure condition. The model can also be used to automatically calculate the LGE of the concrete per unit volume by

Table 3 Concrete mixes proportions for 1 m^3 (kg)

Mixes	M1 (0-0-0)	M2 (50-0-0)	M3 (0-50-0)	M4 (0-0-50)	M5 (50-0-50)	M6 (0-50-50)	M7 (0-0-100)	M8 (50-0-100)	M9 (0-50-100)
Fine sand (kg)	604.7	604.7	604.7	604.7	604.7	604.7	604.7	604.7	604.7
Natural aggregate 10mm (kg)	464.4	464.4	464.4	232.2	232.2	232.2	0	0	0
Natural aggregate 20mm (kg)	928.8	928.8	928.8	464.4	464.4	464.4	0	0	0
Recycled aggregate 10mm (kg)	0	0	0	232.2	232.2	232.2	464.4	464.4	464.4
Recycled aggregate 20mm (kg)	0	0	0	464.4	464.4	464.4	928.8	928.8	928.8
Cement (type GP) (kg)	630.1	315.0	315.0	630.1	315.0	315.0	630.1	315.0	315.0
Fly ash (kg)	0	315.0	0	0	315.0	0	0	315.0	0
Slag (GBFS)	0	0	315.0	0	0	315.0	0	0	315.0
Water (liter)	1400	1400	1400	1400	1400	1400	1400	1400	1400
Water/binder	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Compressive strength (MPa)	31.9	25.7	31.9	34.8	29.8	27.3	40.8	36.8	33
GHG emissions (kg CO_2-e/m^3)	622.2	230.8	249.1	620.4	228.9	247.3	618.5	227.1	245.4
EGHG kg/kg	0.15	0.06	0.07	0.15	0.06	0.07	0.15	0.06	0.07

Table 5 Shrinkage reversible and irreversible percentages

Mixes	Reversible	Irreversible
M1 (0-0-0)	55.0%	45.0%
M2 (50-0-0)	64.5%	35.5%
M3 (0-50-0)	57.6%	42.4%
M4 (0-0-50)	22.0%	78.0%
M5 (50-0-50)	42.2%	57.8%
M6 (0-50-50)	53.5%	46.5%
M7 (0-0-100)	52.2%	47.8%
M8 (50-0-100)	23.5%	76.4%
M9 (0-50-100)	14.6%	85.4%

Table 6 Summary of compressive strength test results (mean values) and standard deviations in parentheses

Mixes	7 days	14 days (MPa)	28 days
M1 (0-0-0)	20.6 (2.19)	25.9 (2.90)	31.9 (1.92)
M2 (50-0-0)	16.2 (0.36)	21.5 (0.51)	25.7 (2.03)
M3 (0-50-0)	18.7 (1.29)	21.2 (1.50)	31.9 (0.21)
M4 (0-0-50)	25.0 (1.95)	27.3 (1.50)	34.8 (0.18)
M5 (50-0-50)	19.8 (0.08)	25.2 (1.65)	29.8 (0.27)
M6 (0-50-50)	17.6 (1.20)	20.6 (0.64)	27.3 (0.09)
M7 (0-0-100)	34.5 (1.90)	36.5 (0.63)	40.8 (0.29)
M8 (50-0-100)	25.8 (2.61)	29.6 (0.52)	36.8 (0.06)
M9 (0-50-100)	22.3 (1.82)	25.1 (1.00)	33.0 (0.15)

specifying the required quantity of cement, fine aggregate, coarse aggregate, and water as inputs. The recycled concrete LGE analyses included five phases, as follows (Le et al., 2018):

1) Greenhouse gas footprint of concrete extraction and production;

2) Greenhouse gas emissions for transportation and pumping;

3) Greenhouse gas emissions for demolition;

4) Greenhouse gas emissions in disposal;

5) Greenhouse gas emissions for recycling and reusing.

3 Results

3.1 Shrinkage

Figure 1 shows the shrinkage development of the samples, and Table 5 summarizes their reversibility and irreversibility.

The results of shrinkage test (irreversible) demonstrated that the recycled concrete has slightly higher shrinkage than that of the normal concrete. The sample reimmersed in water recovers approximately 64.5% of the lost volume, which was higher compared with that of the control mixture that regained only 55%. Therefore, curing the concrete reduces the effect of deformation caused by shrinkage. According to the shrinkage test results, the mixture with 50% fly ash improved the shrinkage characteristics and made it more effective than the normal mixture. The shrinkage value decreased by approximately 500 μm when fly ash was added.

According to the shrinkage results, 50% recycled aggregate with 100% cement provided reasonable results compared with the control concrete. Therefore, when the samples were reimmersed in water, the recovered volume rate of 78%, which was higher compared with that of the control concrete that regained only 55%, was obtained. A total of 50% of recycled aggregate combined with 50% fly ash presented lower shrinkage results than that of the control concrete. After placing the samples in water, they reabsorbed approximately 53%.

3.2 Compressive strength and rupture modulus

The results of compressive strength at 7, 14, and 28 days and rupture modulus at 28 days are summarized in Tables 6 and 7, respectively. Figure 2 shows the development of compressive strength at 7, 28, and 90 days with different recycled aggregate contents of 0%, 50%, and 100%, respectively. The results showed that the compressive strength for recycled the aggregate content of 50% increased by 21% at 7 days, 5% at 14 days, and 9% at 28 days. The compressive strength increased by 67% at 7 days, 40% at 14 days, and 28% at 28 days with the incorporation of 50% recycled aggregate and 100% recycled aggregate. However, the recycled aggregate is beneficial only when the quantity is $< 30\%$ (Sim and Park, 2011).

This increase in the compressive strength can be due to the methods of mixing and the quality of the recycled aggregate (Kong et al., 2010). Conversely, the rupture modulus results decreased by 8%. However, the mixture with 50% recycled aggregate and 50% slag provided better compressive strength result than that obtained using the natural aggregate combined with 50% slag but similar to those of the control one and those with low rupture modulus results of approximately 6%. Therefore, the recycled aggregate may generate an effective result with slag as long as its quantity is $> 50\%$. A similar result was also discussed by a previous research (Gesoğlu and Guneyisi, 2011). In a mixture with 50% recycled aggregate and 50% fly ash, the compressive strength and rupture modulus results reduced by approximately 15% and 17%, respectively.

Figures 3 and 4 present the influence of fly ash and slag on the compressive strength at 7, 14, and 28 days relative to the reference mixture, respectively. The incorporation of fly ash (50%) may have caused the decrease in the compressive strength of 22% at 7 days, 17% at 14 days,

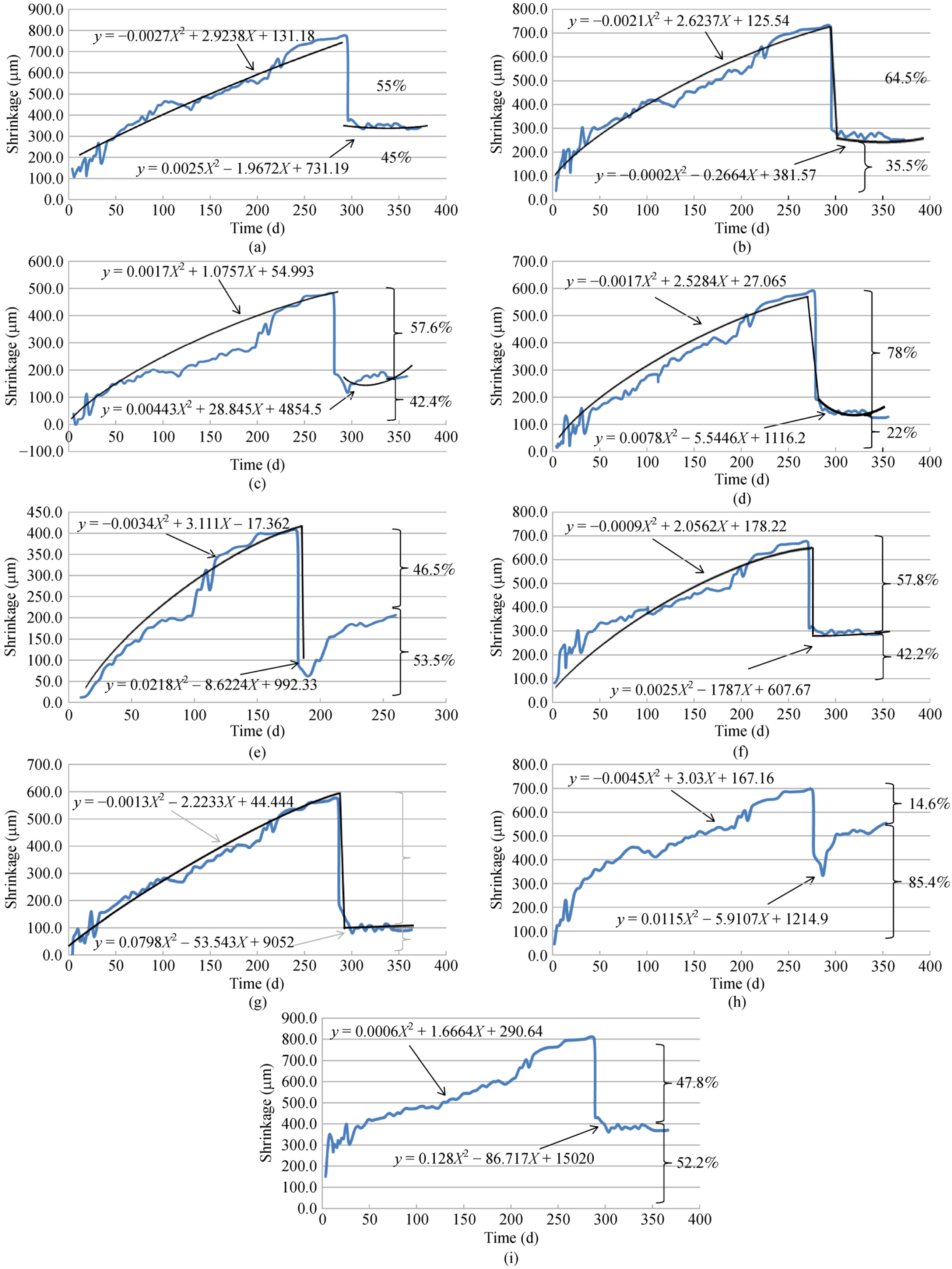


Fig. 1 Drying shrinkage test for (a) M1, (b) M2, (c) M3, (d) M4, (e) M5, (f) M6, (g) M7, (h) M8 and (i) M9

Table 7 Modulus of rupture at 28 days

Mixes	Modulus of rupture (MPa)
M1 (0-0-0)	4.14
M2 (50-0-0)	3.46
M3 (0-50-0)	3.02
M4 (0-0-50)	3.81
M5 (50-0-50)	3.86
M6 (0-50-50)	3.44
M7 (0-0-100)	4.10
M8 (50-0-100)	4.66
M9 (0-50-100)	3.21

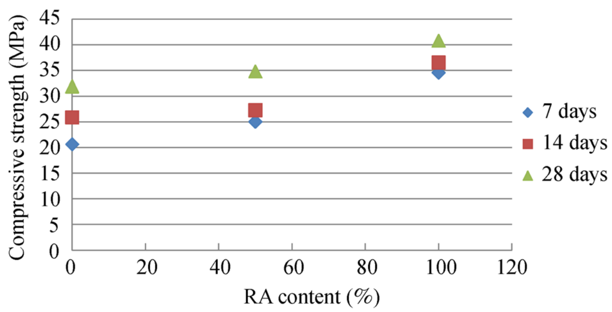


Fig. 2 Compressive strength versus recycled aggregate content

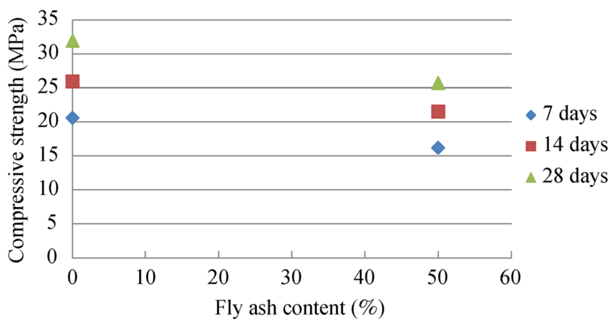


Fig. 3 Compressive strength versus fly ash content

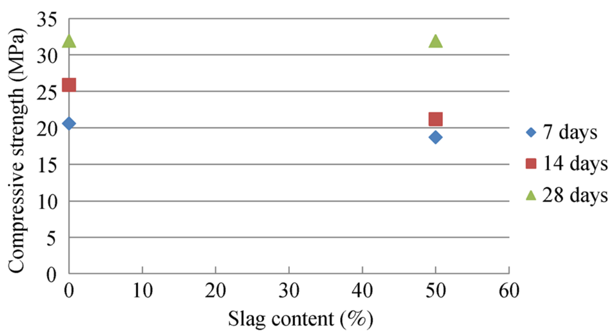


Fig. 4 Compressive strength versus slag content

and 21% at 28 days. Concrete strength decreased over time due to the slow pozzolanic reaction between fly ash and cement's hydration component. Similar performance was reported in others studies (Kurad et al., 2017; Golewski, 2018). The incorporation of 50% slag resulted in a compressive strength reduction only at 7 and 14 days of 12% and 17%, respectively. Figure 5 shows that the incorporation of 100% of recycled aggregate in place of natural aggregate with 100% cement produced high strength concrete in compressive strength, thereby achieving an increase of 30% over the control concrete.

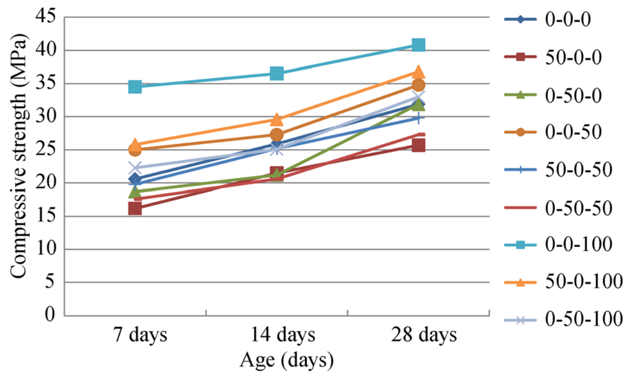
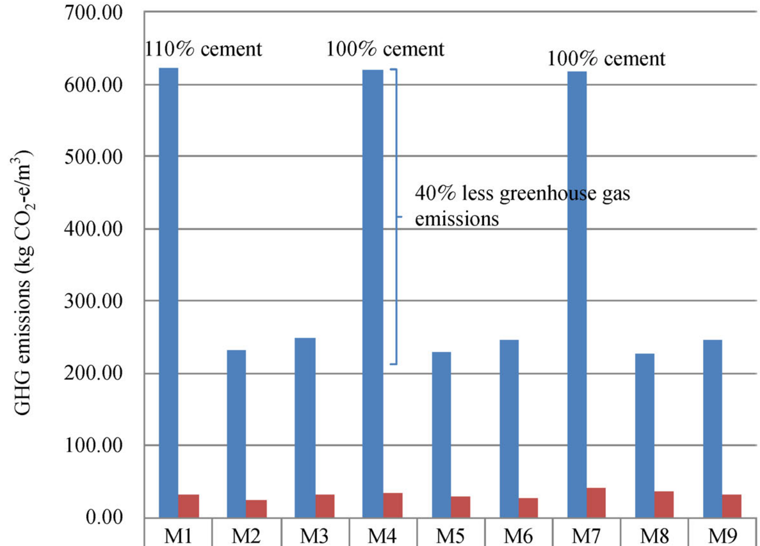


Fig. 5 Influence of slag (50%), fly ash (50%), and recycled aggregate (50% and 100%) contents on compressive strength over time

3.3 Life-cycle greenhouse gas results

The LGE model created by Le et al. (2018) was adopted to evaluate the environmental impact of the concrete mixtures. In a previous study, Le at al. (2018) reported that 40% of fly ash and blast furnace slag replacement within a concrete with identical strengths (50 MPa) presented the quantity of greenhouse gas emissions of 321.33 and 336.64 kg CO_2-eq/m^3, respectively. The concrete with 100% ordinary Portland cement presented the greenhouse gas emissions of 426 kg CO_2-eq/m^3, 30% higher than the mixture incorporating 40% of fly ash + blast furnace slag and similar compressive strength.

Figure 6 shows the results of the greenhouse gas emissions of each concrete mixture with different incorporation levels of fly ash, slag, and recycled aggregate. The amount of greenhouse gas emissions decreased by 40% for the mixture with 50% fly ash and slag replacement. The mixtures (M4 and M7) containing 100% of cement Portland and 50% and 100% recycled aggregate, respectively, present an insignificant GHG emission reduction, showing that the cement replacement is the most important factor in terms of GHG emissions. This finding aligns with others researches reporting that the cement content is the parameter that effectively influences greenhouse gas emissions amount (Yu et al. 2017; Le at al. (2018)). According to Wang et al. (2013), the five driving



	M1	M2	M3	M4	M5	M6	M7	M8	M9
GHG emissions (kg CO_2-e/m^3)	622.28	230.83	249.16	620.43	228.98	247.31	618.59	227.14	245.46
Compressive strength (MPa)	31.9	25.7	31.9	34.8	29.8	27.3	40.8	36.8	33

Fig. 6 Greenhouse gas emissions and compressive strength of concretes with the incorporation of fly ash, slag, and recycled aggregate

factors that induce changes in the greenhouse gas emissions derived from cement production include energy emission factor, energy structure, energy intensity, cement production activity, and clinker production activity.

As shown in Fig. 7, the relationship between the compressive strength (28 days) and greenhouse gas emissions is unclear. The greenhouse gas emission depends on the type of the concrete constituents rather than concrete strength. For the same compressive strength, the greenhouse gas emissions decrease with the incorporation of fly ash or slag.

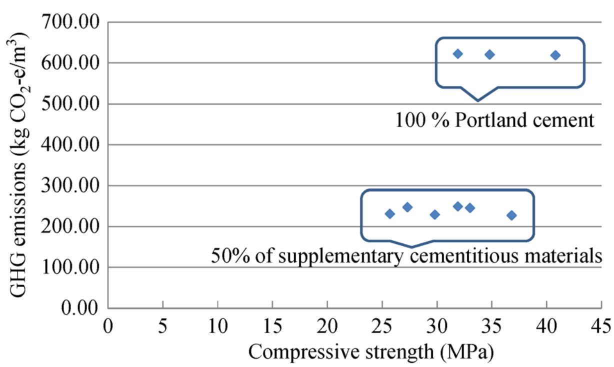


Fig. 7 Greenhouse gas emissions versus compressive strength of concrete with the incorporation of fly ash, slag, and recycled aggregate

Figure 8 shows the classification of the produced concretes from low to high relationship between concrete strength and greenhouse gas emissions. In terms of the environmental impact, the results indicated that the best

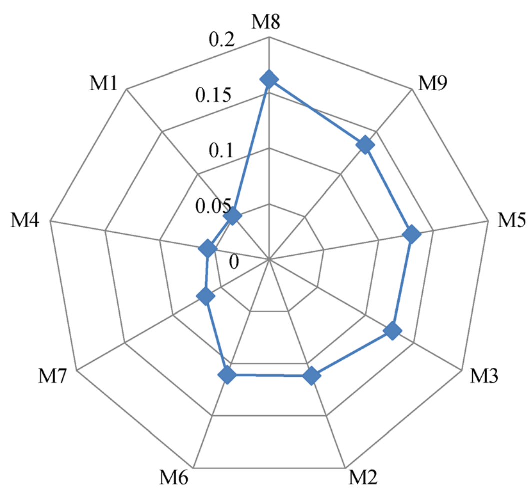


Fig. 8 Classification of the concrete mixes according to the compressive strength (28 days)/greenhouse gas emissions ratio

concrete was M8 (50% fly ash + 100% recycled aggregate). The worst scenario was obtained when 100% Portland cement and 100% (M1) natural aggregate were used.

4 Discussion

This paper aimed to evaluate the use of fly ash and slag with recycled aggregate for concrete production. An experimental program was conducted by replacing recycled aggregate (0%, 50%, and 100%), slag (0% and

50%), and fly ash (0% and 50%) for concrete production and performing compressive strength, rupture modulus, and shrinkage tests. The 100% recycled aggregate sample with 50% fly ash produced the most effective concrete in terms of the rupture modulus, thereby presenting a strength gain of 12%. These study results agreed with some research findings, and these findings can be explained by the recycled aggregate bleeding of absorbed water, thereby improving the quality of ITZ (Ryu, 2002).

The results of this study demonstrated that slag and fly ash were effective cementitious supplementary materials that can improve the concrete properties when added to the cement. The results showed that the slag was slightly more efficient than fly ash as long as its amount is $\leqslant$50%. The incorporation of 50% fly ash improved the shrinkage characteristics and made it more effective than that obtained with reference mixture samples. The results indicated that the concrete strength increased when the amount of the recycled aggregate increased. This performance can be related either to the high quality of recycled aggregate or to the mixing method. The combination of recycled aggregates, fly ash, and slag was suitable to produce high-quality recycled concrete. Berndt (2009) argued that 50% slag is not only extremely beneficial but also provides the best concrete strength results of 45.7 and 49.8 MPa for 28 and 84 days, respectively. The difference between the results of the study of Berndt (2009) and the present study can only be concluded from the different qualities and properties of the slag used for the concrete production.

In terms of the environmental impact analyses, material selection is crucial. The obtained results demonstrated that the cement replacement by SCM (fly ash and slag) significantly decreased the greenhouse gas emission compared with the individual incorporation of recycled aggregate (50% and 100%). In conclusion, the concrete mixes combining both compressive strength and greenhouse gas emissions can be optimized because the best scenario in this study was obtained by the concrete mixture M8. According to Kurad et al. (2017), the relationship between compressive strength and environmental impacts of production, such as global warming potential, can be considered to produce concrete and evaluate the main differences related to environmental impact and concrete strength.

5 Conclusions

In addition to the significant benefits and technical viability of the use of eco-friendly materials combined with LGE analyses, this research promotes the advantages of this material when a sustainable construction scenario is needed. The industry management professionals can also take advantage of the credit points gained from the materials category listed in many green-building rating systems, such as the Green Star Environmental Rating System by selecting eco-friendly materials because recycled concrete was produced with fly ash and slag.

References

Alcas (2017). AusLCI— The Australian Life Cycle Inventory Database initiative. AusLCI Project

AS 1012.13 (2014). Methods of testing concrete—determination of the drying shrinkage of concrete specimens. Australian Standards, Australian Government

AS 1012.17 (2014). Methods of testing concrete—determination of the static chord modulus of elasticity and Poisson's ratio of concrete specimens. Australian Standards, Australian Government

AS 1012.2 (2014). Methods of testing concrete—determination of concrete mixes in the laboratory. Australian Standards, Australian Government

AS 1012.9 (2014). Methods of testing concrete—determination of the compressive strength of concrete specimens. Australian Standards, Australian Government

Berndt M L (2009). Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate. Construction & Building Materials, 23(7): 2606–2613

Cement Australia (2016). Chemical component for material, Cement Australia, Queensland, Australia. http://www.cementaustralia.com.au/

Cetin B, Aydilek A H, Guney Y (2012). Leaching of trace metals from high carbon fly ash stabilized highway base layers. Resources, Conservation and Recycling, 58: 8–17

Chau C K, Leung T M, Ng W Y (2015). A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. Applied Energy, 143: 395–413

EPA (2016). Life Cycle GHG Accounting Versus GHG Emission Inventories. https://www.epa.gov/sites/production/files/2016-03/documents/life-cycle-ghg-accounting-versus-ghg-emission-inventories10-28-10.pdf

Etxeberria M, Mari A R, Vazquez E (2007). Recycled aggregate concrete as structural material. Materials and Structures, 40(5): 529–541

Gesoğlu M, Guneyisi E (2011). Perneability properties of self-compacting rubberized concrete. Construction & Building Materials, 25(8): 3319–3326

Golewski G L (2018). Green concrete composite incorporating fly ash with high strength and fracture toughness. Journal of Cleaner Production, 172: 218–226

Hansen T C (1992). Recycling of demolished concrete and masonry: Report of technical committee 37-DRC, demolition and reuse of concrete. The International Union of Testing and Research Laboratories for Materials and Structures, London, E&FN Spon

Hemalatha T, Ramaswamy A (2017). A review on fly ash characteristics – Towards promoting high volume utilization in developing sustainable concrete. Journal of Cleaner Production, 147: 546–559

Kaur G, Siddique R, Rajor A (2012). Properties of concrete containing fungal treated waste foundry sand. Construction & Building

Materials, 29: 82–87

Kong D, Lei T, Zheng J, Ma C, Jiang J (2010). Effect and mechanism of surface-costing pozzzalanics materials around aggregate on properties and ITZ microstructure of recycled aggregate concrete. Construction Technology, 24: 701–708

Kou S, Poon C S, Chan D (2008). Influence of fly ash as a cement addition on the hardened properties of recycled aggregate concrete. Materials and Structures, 41(7): 1191–1201

Kou S, Zhan B, Poon C S (2012). Feasibility study of using recycled fresh concrete waste as coarse aggregates in concrete. Construction & Building Materials, 28(1): 549–556

Kou S C, Poon C S, Agrela F (2011). Comparisons of natural recycled aggregate concretes prepared with the addition of different mineral admixtures. Cement and Concrete Composites, 33(8): 788–795

Kou S C, Zhan B J, Poon C S (2014). Use of a CO_2 curing step to improve the properties of concrete prepared with recycled aggregates. Cement and Concrete Composites, 45: 22–28

Kumanayake R, Luo H (2018). Life cycle carbon emission assessment of a multi-purpose university building: A case study of Sri Lanka. Frontiers of Engineering Management, 5(3): 381–393

Kurad R, Silvestre J, Brito J, Ahmed H (2017). Effect of incorporation of high volume of recycled concrete aggregates and fly ash on the strength and global warming potential of concrete. Journal of Cleaner Production, 166: 485–502

Le K N, Tam V W Y, Cuong N T, Jiayuan W, Blake G (2018). Life-cycle greenhouse gas emission analyses for green star's concrete credits in Australia. IEEE Transactions on Engineering Management: 1–13

Levy S M, Helene P (2004). Durability of recycled aggregate concrete: A safe way to sustainable development. Cement and Concrete Research, 34(11): 1975–1980

Mater M, Georgy M E, Ibrahim E (2004). Towards a more applicable set of sustainable construction practices. In: International Conference of Future Vision and Challenges for Urban Development, CE16: 1–12

Mehta P, Monteiro P J M (2005). Concrete Microstructure, Properties and Materials. New York: McGraw-Hill

Olorunsogo F T, Padayachee N (2002). Performance of recycled aggregate concrete monitored by durability indexes. Cement and Concrete Research, 32(2): 179–185

Padmini A K, Ramamurthy K, Mathews M S (2008). Influence of parent concrete on the properties of recycled aggregate concrete. Construction & Building Materials, 23(2): 829–838

Poon C S, Chan D (2007). The use of recycled aggregate in concrete in Hong Kong. Resources, Conservation and Recycling, 50(3): 293–305

Qiu J, Qin D, Tng S, Yang E H (2014). Surface treatment of recycled concrete aggregates through microbial carbonate precipitation. Construction & Building Materials, 57: 144–150

RMCG (2010) Consultants for Business, Community and Environment. Sustainable Aggregates – CO_2 Emission Factor Study, Bendigo, Australia, 1–16

Ryu J S (2002). An experimental study on the effect of recycled aggregate on concrete properties. Magazine of Concrete Research, 54 (1): 7–12

Sandanayake M, Zhang G, Setunge S, Li C Q, Fang J (2016). Models and method for estimation and comparison of direct emissions in building construction in Australia and a case study. Energy and Building, 126: 128–138

Sharma B, Grant T (2015). Life Cycle Inventory of Cement and Concrete produced in Australia. Life Cycle Strategies Pty Ltd, Melbourne, Australia, 1–48

Sim J, Park C (2011). Compressive strength and resistance to chloride ion penetration and carbonation of recycled aggregate concrete with varying amount of fly ash and fine recycled aggregate. Waste Management (New York, N.Y.), 31(11): 2352–2360

Tam V W Y (2009). Comparing the implementation of concrete recycling in the Australian and Japanese construction industries. Journal of Cleaner Production, 17(7): 688–702

Tam V W Y, Gao X F, Tam C M (2005). Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach. Cement and Concrete Research, 35(6): 1195–1203

Tam V W Y, Tam C M, Wang Y (2007). Optimization on proportion for recycled aggregate in concrete using two-stage mixing approach. Construction & Building Materials, 21(10): 1928–1939

Tam V W Y, Wang Z B, Tao Z (2014). Behaviour of recycled aggregate concrete filled stainless steel stub columns. Materials and Structures, 47(1-2): 293–310

Wang Y, Zhu Q H, Geng Y (2013). Trajectory and driving factors for GHG emissions in the Chinese cement industry. Journal of Cleaner Production, 53: 252–260

Xiao J, Li J, Zhang C (2005). Mechanical properties of recycled aggregate concrete under uniaxial loading. Cement and Concrete Research, 35(6): 1187–1194

Yu J, Cong L, Leung C K Y, Li G Y (2017). Mechanical properties of green structural concrete with ultrahigh-volume fly ash. Construction & Building Materials, 147: 510–518

Zhang J, Shi C, Li Y, Pan X, Poon C S, Xie Z B (2015). Influence of carboanted recycled concrete aggregate on properties of cement mortar. Construction & Building Materials, 98: 1–7