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Shear behavior of reinforced concrete beams using treated recycled concrete aggregate

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HIGHLIGHTS

- Surface treatment method is used on recycled coarse aggregate (RCA).
- The treatment included pre-soaking in acid and impregnating with sodium metasilicate pentahydrate solution.
- Using treated RCA increases the compressive strength of concrete compared with untreated RCA.
- The treated RCA beams show an increase on shear strength compared with untreated RCA and control beams.
- The treated RCA beams show identical crack propagation pattern compared with untreated RCA and control beams.

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ABSTRACT

The shear behavior of ten full scale reinforced concrete beams that were constructed from natural aggregate, recycled aggregate and treated recycled aggregate was experimentally and analytically studied. All beams were constructed without stirrups and with 50% and 100% recycled aggregate. The beams were tested for a shear span-to-depth ratio (a/d) equal to 2.0 and 3.0. The performance of recycled aggregate was improved through enhancement treatment methods. The recycled aggregate was pre-soaked in hydrochloric acid (HCl) for 24 h to remove adhered mortars attached to original recycled aggregates, and then they were impregnated with sodium metasilicate pentahydrate solution for one hour to coat their surfaces. The behavior of the shear-critical beams was studied through reporting the load-deflection curves, ultimate load values, and crack propagation during static tests. The experimental shear capacities of the beams were compared with theoretical values from different international codes and fracture mechanics approaches. The experimental results showed that in general using treated recycled aggregate improved slightly the shear capacity of the beams in comparison with natural and untreated recycled aggregate. Furthermore, the shear strength comparisons showed that the treated recycled aggregate beams were considered more conservative compared to the natural and untreated recycled aggregate beams regardless of the shear span-to-depth ratio.

1. Introduction

Concrete is one of the most used materials on earth. The demand for concrete as a construction material was very high in the past and will continue to be in future. Concrete uses a significant amount of non-renewable materials and resources especially natural aggregate. Furthermore, the biggest component from building demolition operations is concrete. The wastes from construction and demolition are increasing to a high level which causes an increase in landfill areas. This leads to air and ground water pollutions which will result in negative impact on environment. In addition, the economy of the countries will be negatively affected because of millions of dollars that are paid every year to: (1) remove the concrete wastes from construction and demolition sites; (2) transport the concrete wastes out of the major cities to the proposed landfill areas; and (3) perform needed procedures to bury the concrete wastes. Matias et al. [1] pointed out that the amount of demolition waste in European Union is approximately 1 ton per capita and the overall amount produced is more than 450 million tons per year. However, this amount of demolition wastes is increasing to intolerable rates in other parts of the world such as Middle East due to the ongoing wars at those countries. Unfortunately, the record on amount of demolition wastes is not

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Table 1
Chemical composition of cement and sodium metasilicate pentahydrate.

Material	Chemical composition (%)							
	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	H_2O	pH	Specific gravity (g/cm^3)
Cement	21.36	5.57	3.35	62.5	–	–	–	3.10
Sodium metasilicate pentahydrate	28.5	–	–	–	28.5	45.5	12.5	0.90

available in those countries and there are no sufficient financial resources to get rid of the wastes which are leading to a very negative impact on environment, human health, and safety.

One of the issues that can help the environment and save the non-renewable natural resources is to use recycled coarse aggregate (RCA) in construction. Recycling concrete from structures demolition provides a number of advantages: (1) reduce production and consumption of non-renewable natural resources such as natural aggregate; (2) reduce the landfill areas; (3) improve the environment by minimizing the air and ground water pollutions; and (4) save millions of dollars in the construction industry.

Many researchers have conducted in the last year's studies on the effect of using RCA in production of concrete [2–9]. The results of those works reveal that the quality of recycled aggregate is usually lower than that of natural aggregate due to remaining mortar particles, surface cracks, and higher water absorption and porosity of RCA. This will cause negative effects on the mechanical properties, workability, air content and durability of fresh and hardened concrete [10–12]. To overcome this issue, several studies were conducted on improving the performance of RCA through enhancement treatment methods. Shi et al. [11] provided a comprehensive literature review for such methods. The authors divided the treatment methods into: (1) mechanical and heat grinding [13]; (2) pre-soaking in water or acid [14,15]; (3) polymer emulsion [16,17]; (4) pozzolan slurry [18]; (5) Calcium Carbonate bio-deposition [19]; (6) Sodium silicate solution [20]; and (7) Carbonation [21,22]. Pre-soaking in acid can be considered one of the most efficient, environmental friendly and feasible methods for improving the mechanical properties and durability of RCA. Tam et al. [23] and Ismail and Ramli [24] reported that the mechanical properties and water absorption of RCA have improved significantly when the cement mortar remains of recycled aggregate were removed by pre-soaking in acid and impregnating with calcium metasilicate.

Most of the published work in literature investigated the properties of fresh and hardened recycled aggregate concrete in laboratory environment using concrete cubes, cylinders, and prisms. Mapping laboratory results to real life is an important consideration. Few studies were reported on structural behavior of full scale structural elements [25–30]. Arezoumandi et al. [31] studied the shear strength of twelve full scale beams constructed with 100% RCA. The load-deflection response and crack pattern of RCA beams were identical to conventional concrete beams, while the shear strength of RCA beams were 12% lower compared to conventional concrete beams. Fathifazl et al. [32] proposed an Equivalent Mortar Volume (EMV) method that provides a special mix design to construct RCA beams. The results showed that the shear capacity of RCA beams is equivalent to conventional concrete beams. Choi et al. [33] studied the shear strength of twenty beams with different span-to-depth ratios, longitudinal reinforcement ratios and RCA replacement ratios. They concluded that the shear strength of RCA beams was lower than that of conventional concrete beams with same span-to-depth ratio and reinforcement ratio. Fonteboa et al. [34] studied the effect of adding 8% silica fume on ultimate shear strength of eight beams with 50% RCA. The results showed that there was no significant difference in deflection and ultimate shear strength between RCA and conventional concrete beams, but the splitting cracks along the tension reinforcements were mitigated by the addition of silica fume.

Fig. 1. Photo of chunks of concrete after crushing process.

Table 2
Sieve analysis of coarse aggregates.

Aggregate	Aggregate passing (%) according to sieve size (mm)				
	19	12.5	9.5	4.75	2.36
Natural coarse	100	69.2	43	0.7	0.2
RCA	100	68.1	41	0.6	0.1

Based on the extensive search in the literature; it is obvious that there is a great need to study the structural behavior of full scale members that are constructed using enhanced treated recycled aggregate because this area is still an open field of study. The objective of this paper is to study experimentally and analytically the shear behavior of full scale reinforced concrete beams that are constructed from normal aggregate, recycled aggregate and treated recycled aggregate. The beams are constructed with 50% and 100% RCA. The performance of RCA is improved through enhancement treatment methods. The RCA is pre-soaked in hydrochloric acid (HCl) for 24 h to remove adhered mortars attached to original RCA aggregates, and then they are impregnated with sodium metasilicate pentahydrate solution for one hour to coat their surfaces. The beams are tested for a shear span-to-depth ratio (a/d) equal to 2.0 and 3.0. The behavior of the shear-critical beams is studied through reporting the load-deflection curves, ultimate load values, and crack propagation during static tests. The experimental shear capacities of the beams are compared with theoretical values from different international codes and fracture mechanics approaches. According to the best author's knowledge, this is the first paper that studies the shear behavior of full scale reinforced concrete beams that are constructed with treated RCA.

Although it is expected that this surface treatment process will take an extra amount of time for large quantities of RCA; this can be considered reasonable because this process is expected to be very effective on enhancing the shear capacity of the reinforced concrete beams compared to untreated RCA beams. The using of treated RCA in construction will result in positive impact on environment and can be considered economically more feasible in comparison to the amount of money paid for landfilling processes. A detailed feasibility study for using treatment of RCA is out of