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Review Article

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Durability of concrete made with recycled aggregates- Review

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Abstract Due to the increasing demolition of existing civil engineering infrastructures, as well as the building industry's sustainability and carbon reduction ambitions, the necessity to use recycled aggregates from construction and demolition wastes for new projects cannot be overstated. The rapidly expanding construction industry necessitates the use of recycled aggregates to substitute natural aggregates for sustainability reasons and to save the environment from mining operations. Many studies have been conducted over the last few decades on the use of recycled aggregate (RA) produced from building and demolition wastes to make concrete products. This paper presents the findings of the durability performance of concrete made with recycled aggregates. The amount of recycled aggregates, water cement ratio, and attached mortar are all aspects that contribute to the durability performance of recycled aggregate concrete. In general, the durability performance of the recycled aggregate concrete is low compared the normal concrete made with virgin aggregates. However, research have developed numerous strategies for increasing the recycled aggregate concrete performance, such as the use of fly ash, silica fume, and pre-treatment of recycled aggregates. This research will conduct a comprehensive analysis of the durability of recycled aggregate concrete from various studies for potential high-value applications in the construction sector.

Keywords Durability, recycled aggregate, carbon reduction, industry's sustainability

Introduction

The use of recycled aggregate (RA) obtained from building and demolition waste is promising in the production of fresh concrete for the aim of satisfying the construction industry's sustainability and carbon reduction targets. The use of recycled aggregates concrete in new construction might reduce the requirement for virgin limestone aggregates by 60% and cut carbon emissions by 15%-20% [1]. If construction wastes are not recycled and utilised, it will cause major environmental damage; additionally, its disposal on site will take an ever-growing quantity of farmland. As a result, effective recycling and reuse of building debris is an essential technical challenge that must be solved to ensure sustainable growth. Recycled aggregate concrete (RAC) will become an essential component of building materials in the future as a novel material that fits the material-saving needs of green buildings and embodies the notion of sustainable development [2, 3]. It is estimated that in 2018, the UK produced 67.8 million tonnes of non-hazardous C&D waste, of which 62.6 million tonnes were recovered as indicated in Table 1, this equates to a 93.8 percent recovery rate [4]. The necessity to utilise recovered waste in the building sector without sacrificing cost and performance is a major challenge. The use of recycled materials reduces the requirement for material extraction, which would otherwise lead to resource depletion and other environmental issues. Despite the environmental benefits of recycling construction, post-consumer, and industrial waste and its eventual use in construction, research studies have revealed that recycled materials have been underutilised in construction projects, and their acceptance in the construction industry remains low [5]. This low acceptance level was caused by the uneven quality of the source, which was affected by a variety of factors such as different building and demolition methods, levels of segregation, age, deterioration, and so on. This causes scepticism about the quality of these secondary materials and adds to the perception that C&D recycled aggregates are low-value by default [6].

Table 1: Recovery rate from non-hazardous construction and demolition waste, UK and England, 2010-18 [4]

million tonnes and % rate

	UK			England		
	Generation	Recovery	Recovery rate	Generation	Recovery	Recovery rate
	M tonnes	M tonnes	%	M tonnes	M tonnes	%
2010	59.2	53.1	89.7%	53.6	49.4	92.2%
2011	60.2	55.0	91.4%	54.9	50.8	92.5%
2012	55.8	50.8	91.1%	50.5	46.4	92.0%
2013	57.1	52.0	91.2%	51.7	47.6	92.0%
2014	61.5	56.3	91.5%	55.9	51.7	92.4%
2015	63.8	58.0	91.0%	57.7	53.3	92.3%
2016	66.2	60.0	90.7%	59.6	55.0	92.1%
2017	68.7	62.9	91.5%	62.2	57.9	93.1%
2018	67.8	62.6	92.3%	61.4	57.5	93.8%

On the other hand, there is a rising need for natural aggregates, which account for approximately 75% of the concrete weight. According to [7] up to 20 billion metric tonnes of natural aggregates are consumed globally each year. Construction operations consume around 50% of natural resources, 40% of energy, and generate 50% of wastes [8]. As shown in Figure 1, using recycled aggregates (RA) as a structural material has several advantages. Reusing CDW, particularly recycled aggregates, in the production of fresh concrete is an essential step toward sustainability in the building sector.

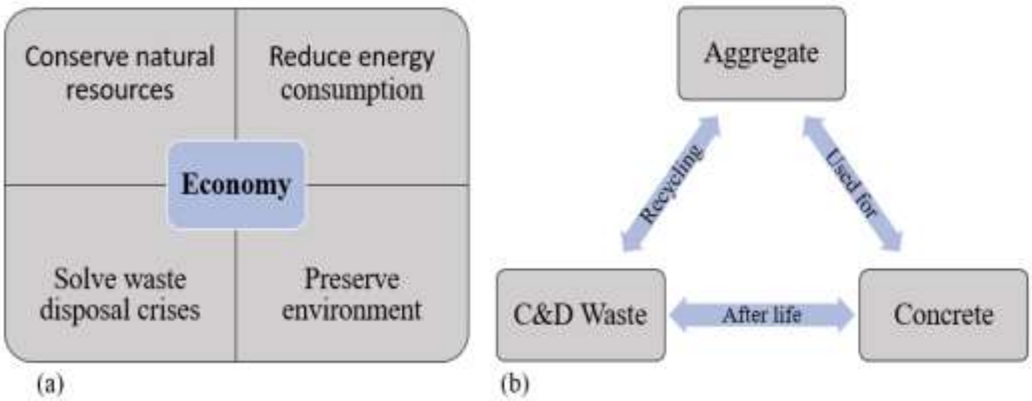

Figure 1: (a) Benefits and (b) Lifecycle of recycled aggregate from CDW [9]

Classification of recycled aggregates

Recycled aggregate is mostly composed of unbound stone (Ru), crushed concrete (Rc), and crushed brick (Rb), with minor amounts of asphalt, glass, lightweight materials, and plaster present. The relative amounts of these three primary components inside recycled aggregate can vary greatly, which in turns affects the concrete performance differently. [10] has methodically addressed this issue by only completely prescribing recycled aggregates standards for concrete applications, requiring recycled aggregate material to possess Rc > 83.5 percent by mass and Rb 5% by mass as shown in Table 1.The constituent of recycled aggregates determine its category based on the specifications made in [11] as shown in Table 1.

Table 1: Categories for constituents of coarse recycled aggregates [11]

Constituent	Content (Percentage by mass)	Category
Rc	≥ 90	Rc_{90}
	≥ 80	Rc_{80}
	≥ 70	Rc_{70}
	≥ 50	Rc_{50}
	<50	$Rc_{Declared}$
	No requirement	Rc_{NR}
Rc + Ru	≥ 95	Rcu95
	≥ 90	Rcu90
	≥ 70	Rcu70
	≥ 50	Rcu50
	<50	$Rcu_{Declared}$
	No requirement	Rcu_{NR}
Rb	≤ 10	Rb_{10-}
	≤ 30	Rb_{30-}
	≤ 50	Rb_{50-}
	> 50	$Rb_{Declared}$
	No requirement	Rb_{NR}

Durability performance of recycled concrete

Many researchers have sought to determine the durability of recycled aggregate concrete and prospective methods of enhancement for structural applications[12-22]. Durability is a particular problem for typical reinforced concrete buildings utilising recycled aggregate concrete because recycled aggregates in their original crushed condition have higher porosity and permeability than natural aggregates and are thus more prone to reinforcement corrosion[15, 17, 19]. Porosity, creep and shrinkage, freeze and thaw, chloride penetration, and water absorption are all performance needs for durability, and a vast number of research studies have been conducted to study these various performance requirements. A variety of strategies for increasing the durability of recycled aggregate concrete have been researched. This paper reviews previous studies on the durability of recycled aggregate concrete and evaluates various strategies of improvement.

Chloride permeation

Figure 2 compares the results of several researchers who conducted rapid chlorine penetration tests (RCPT) on recycled aggregate concrete. The recycled aggregates were not processed after crushing in these tests. The RCPT values range from 1,800 to 8,000 Coulombs and tend to increase as compressive strength decreases. Except for [21], which has a low compressive strength for 100% RA replacement level, most of the RCPT values are classified as low to medium ion permeability according to the criteria in Table 2.

According to Table 2, the results of [13] achieved chloride ion penetration of 1,800-2,500 Coulombs, which fall within the low to medium range. The cement-to-water ratio was 0.45. The low chloride permeability may be due to the use of recycled aggregates after they have been processed by removing the adhered cement matrix.

[21] stated that by using a water cement ratio of 0.45, the Two-Stage Mixing Approach (TSMA) process could be used to achieve RCPT values in the moderate range of 2800 to 3500 C for 20% and 100% replacement, respectively.

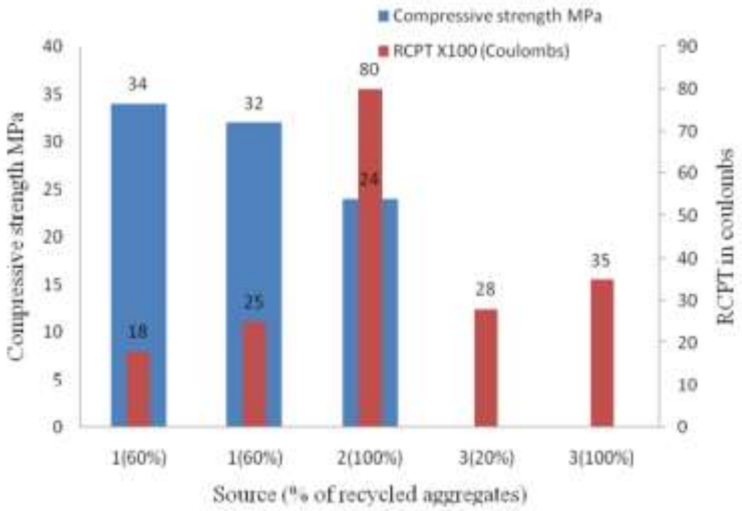

Figure 2: Comparison of RCPT results from different studies; 1.[13]; 2[21]; 3.[22]

Table 2: Ion chloride permeability based on charge passed [23]

Charge Passed (Coulombs)	Chloride Ion Permeability
>4,000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

Drying shrinkage

There is a direct relationship between aggregate drying shrinkage and absorption capacity. The lower the drying shrinkage, the better the durability performance of the concrete. Figure 3 shows that RAC 1-3 with higher compressive strength exhibits lower dry shrinkage than RAC 4-6 with lower compressive strength. As a result, the study concluded that concrete with a higher compressive strength has lower drying shrinkage than low-strength concrete.

Figure 4 shows how the addition of 35% weight of fly ash (FA) as a partial replacement for cement or in addition to cement improved the dry shrinkage of recycled aggregate concrete. Concrete dry shrinkage increased as RA replacement increased. When the existing attached cement matrix on the recycled aggregates is combined with the new cement paste, the volume of paste increases, which increases the drying shrinkage of the resulting concrete.

In summary, using fly ash as a replacement for or addition to concrete reduces drying shrinkage values, which was attributed to the dilution effects of fly ash particles. It is also worth noting that the addition of fly ash reduces drying shrinkage more than when it is used to replace cement. This is because the addition of FA reduces the water cement ratio of the concrete mix from 0.55 to 0.42, indicating that a decrease in w/c reduces concrete drying shrinkage.

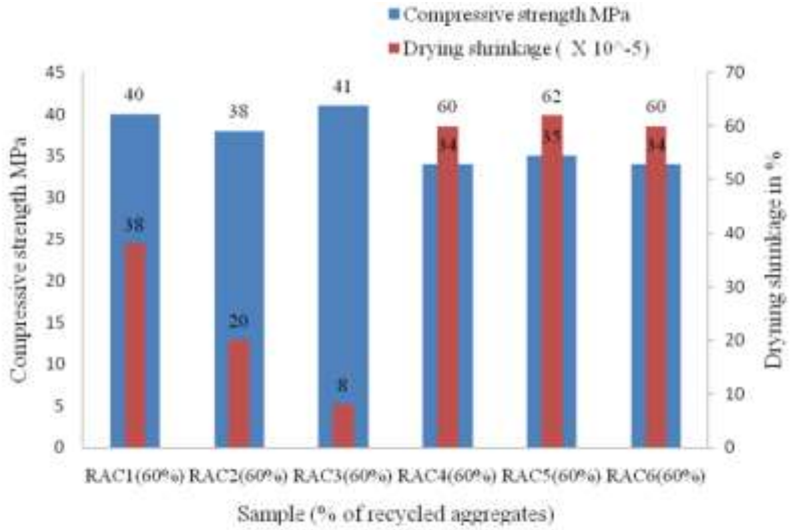

Figure 3: Comparison of drying shrinkage values from different concrete mixes [13]

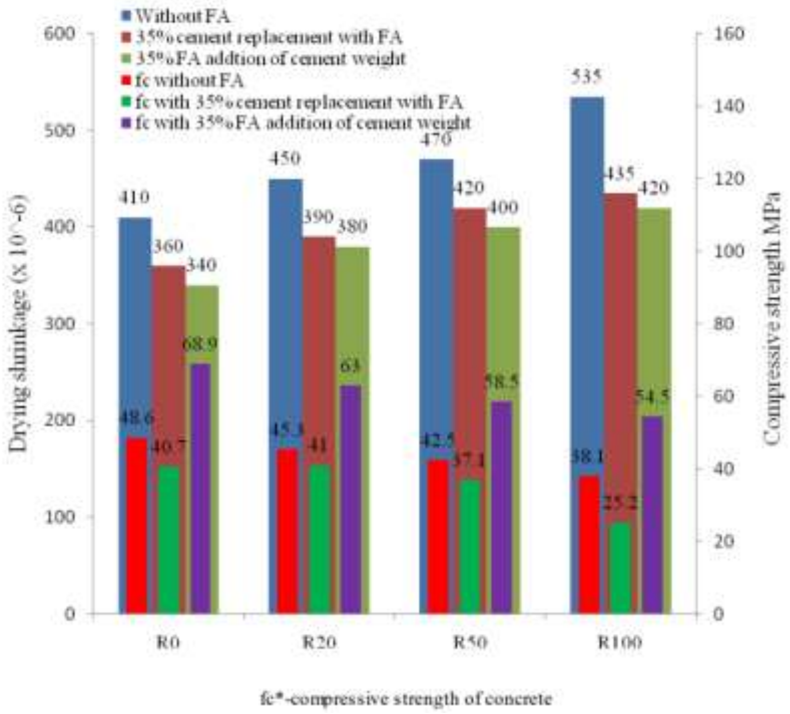

Figure 4: Drying shrinkage of concrete with different recycled aggregate replacement level with and without fly ash (FA)[13]

Carbonation depth

The carbonation depth of recycled aggregate concrete was improved by the addition of 35% in weight of fly ash (FA) as a partial replacement of cement or in addition to cement as shown in Figure 5. It can be observed that the carbonation depth of concrete increased with the increase in recycled aggregate content. However, the use of fly ash as a partial replacement of cement and an addition to cement decreased the carbonation depth of the concrete at different replacement levels.

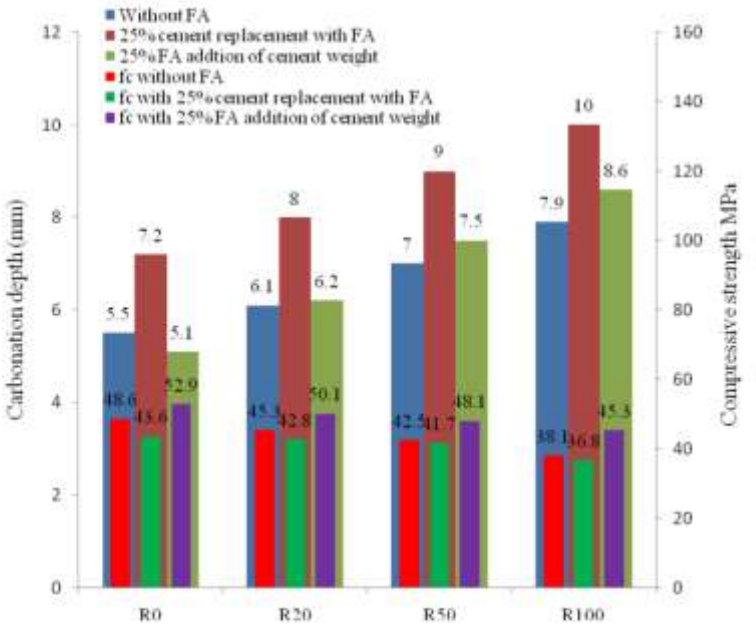

Figure 5: Carbonation depth of concrete with different RA concentration [19]

Creep strain

The creep strain of recycled aggregate concrete was reduced to that of natural aggregate concrete by adding 35% of the weight of fly ash (FA) as a partial replacement of cement or by adding FA to cement, as shown in Figure 6. The deformation of the concrete specimens was found to increase as the recycled aggregate content increased. The increased volume of cement matrix in recycled aggregate concrete compared to natural aggregate concrete was attributed to this. The creep strain of concrete with partial cement replacement with FA was greater than that of concrete with FA addition to cement. This could be due to the use of fly ash, as the addition of cement decreased the W/B ratio, resulting in increased compressive strength, as illustrated in Figure 6.

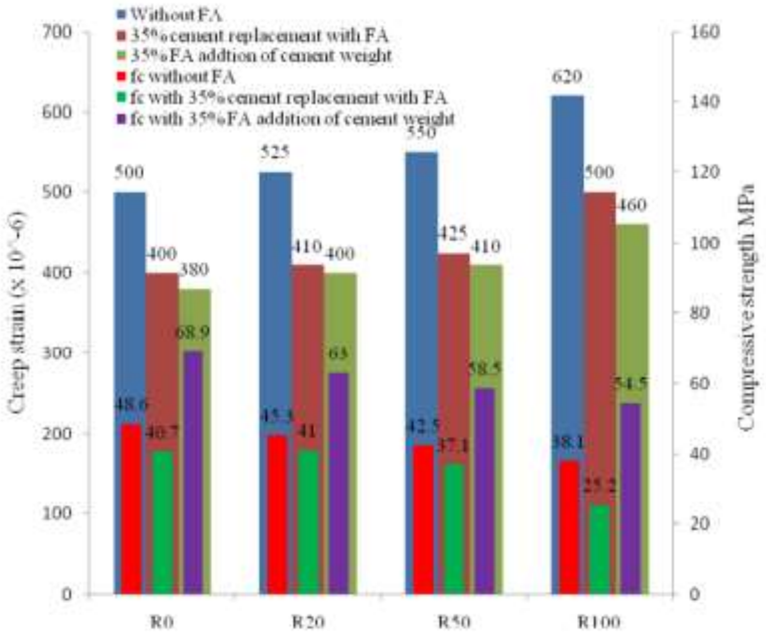

Figure 6 Creep strain of concrete with different recycled aggregate replacement levels with and without fly ash (FA) [19]

Conclusion

In conclusion, the durability of recycled aggregate concrete is inferior to that of natural aggregate concrete. The adhered mortar of recycled aggregates determines and affects the durability of recycled aggregate concrete; the higher the amount of adhered mortar of recycled aggregate, the higher the porosity and water absorption, resulting in poorer durability performance of recycled aggregate concrete. Higher recycled aggregate content and water cement ratio can lead to poor recycled aggregate concrete durability.

The use of fly ash as a partial replacement for, or addition to, cement, on the other hand, improves the durability performance of recycled concrete to that of natural aggregate concrete. Overall, the measures taken to improve the mechanical performance of recycled aggregate concrete were quite impressive, but little thought was given to the cost and feasibility of adopting these methods in the construction industry. For example, adding more cement, silica fume, or fly ash [19, 24, 25] to meet the mix strength requirement increases the cost of the design concrete.

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