INFLUENCE OF TREATED RECYCLED AGGREGATES AS PARTIAL AGGREGATE REPLACEMENT ON PROPERTIES OF CONCRETE

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SCHOOL OF CIVIL ENGINEERING
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by

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ABSTRAK

Dewasa ini, pertumbuhan pesat industri pembinaan telah menjana sejumlah besar sisa pembinaan yang mengakibatkan pencemaran yang kronik kepada alam sekitar. Oleh itu, penggunaan sisa pembinaan sebagai agregat kitar semula (RA) dalam campuran konkrit adalah kaedah yang berkesan daripada aspek ekonomi untuk menangani isu ini. Walau bagaimanapun, konkrit agregat kitar semula (RAC) mempunyai prestasi yang lebih rendah berbanding dengan konkrit biasa (NAC). Oleh itu, rawatan terhadap RA amat diperlukan untuk menambahbaikkan sifat-sifat RAC. Dalam kajian ini, dua objektif telah dinilai iaitu: (a) kecekapan kaedah merawat RA yang berbeza berdasarkan sifat-sifat konkrit, (b) nisbah penggantian RA dirawat asid yang optimum dalam konkrit. RA yang digunakan dalam kajian ini adalah kiub konkrit yang telah dihancurkan dari kilang MDC Batu Kawan. Rawatan RA yang digunakan adalah kaedah salutan buburan simen dan kaedah rawatan asid asetik. Tujuh campuran konkrit telah disediakan dan diuji berdasarkan kebolehkerjaan, ketumpatan, kekuatan mampatan, kekuatan lenturan dan kekuatan tegangan pembelahan. Kajian perbandingan antara dua kaedah rawatan RA telah dilakukan pada nisbah penggantian 20%. Manakala ramalan nisbah penggantian RA terawat yang optimum telah dinilai berdasarkan sifat-sifat konkrit. Keputusan mendedahkan bahawa RAC dengan salutan buburan simen mempunyai sifat mekanikal yang lebih tinggi berbanding dengan RAC terawat asid dan RAC yang tidak dirawat. Tambahan pula, didapati bahawa sifat-sifat mekanikal RAC terawat asid meningkat dengan pertambahan nisbah penggantian RA. Nisbah penggantian RA terawat asid yang optimum dalam RAC telah ditentukan pada 30%. Selain itu, didapati bahawa semua RAC yang dirawat mempamerkan pengurangan dalam kebolehkerjaan konkrit segar.

ABSTRACT

Rapid growth of the construction industry generates a huge amount of construction and demolition waste causing an irreparable damage to the environment. Therefore, application of waste materials as recycled aggregate (RA) in concrete is an efficient and economical method to address the issue. However, recycled aggregate concrete (RAC) has lower performance compared to natural aggregate concrete (NAC). Hence, treatment on the RA is required to improve the properties of the RA and of the resulting concrete. In this study, two objectives were investigated; (a) efficiency of different treatment method of RA based on properties of concrete, (b) the optimum replacement ratio of acid treated RA in concrete. The RA used in this study was crushed concrete cubes from the MDC Batu Kawan concrete batching plant. The RA was treated using cement slurry wrapping method and acetic acid treatment method. Seven concrete mixes were prepared and tested based on workability, density, compressive strength, flexural strength and splitting tensile strength. Comparative study of treatment method was done at a 20% replacement ratio of treated RA. Whereas prediction of optimum replacement ratio of acid treated RAC was examined based on the properties of concrete. The results revealed that cement slurry treated RAC has greater mechanical properties compared to the acetic acid treated RAC and untreated RAC. Furthermore, it was found that the mechanical properties of acid treated RAC improves as the replacement ratio of RA increases. The optimum replacement ratio of acid treated recycled aggregate was determined to be at 30%. However, all treated RAC exhibit a reduction range from 13.75% to 68.75% in workability of the fresh concrete.

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LIST OF ABBREVIATIONS

A-RAC	Acid Treated Recycled Aggregate Concrete
BS	British Standards
CDW	Construction & Demolition Waste
CRA	Coarse Recycled Aggregate
C-RAC	Cement Treated Recycled Aggregate Concrete
FRA	Fine Recycled Aggregate
ITZ	Interfacial Transition Zone
NA	Natural Aggregate
NAC	Natural Aggregate Concrete
OC	Original Concrete
OPC	Ordinary Portland Cement
RA	Recycled Aggregate
RAC	Recycled Aggregate Concrete
U-RAC	Untreated Recycled Aggregate Concrete

CHAPTER 1

INTRODUCTION

1.1 Overview

Sustainable growth in the construction industry has always been a responsibility of the engineers to ensure a prosperous future. Rapid urbanization and industrialization around the world are leading towards an extensive exploitation of natural resources. Meanwhile, the urbanization and industrialization also generated a large amount of construction and demolition waste (CDW) (Bai et al., 2020). Thus, the prospect of recycling construction waste is becoming highly relevant. Research has been conducted on recycled aggregates (RA) to explore their revalorization possibilities in concrete in order to find a feasible alternative disposal for CDW while also conserving the natural resources (Omary et al., 2016). By grinding the construction waste, a new building material which is known as recycled aggregate (RA) is produced to be used as coarse aggregate replacement. Furthermore, as concrete is crushed into smaller particles, a considerable volume of carbon dioxide is absorbed, lowering the CO_2 levels in the atmosphere. Hence, conserving the space for landfills and saving costs (Surendar et al., 2021).

However, the RA has some disadvantages over its counterpart in terms of properties, i.e. recycling RA to make recycled aggregate concrete (RAC) has some drawbacks such as lower compressive strength, lower flexural strength, lower splitting tensile strength and high porosity. The presence of the adhered mortar on the RA may weaken the bond between the RA and fresh mortar paste, resulting in a lower performance RAC. Therefore, to enhance the mechanical properties of recycled aggregate concrete (RAC), several methods had been introduced such as improving concrete mixing process, coating of the RA with pozzolanic materials, adding cementitious materials in the RAC, removing adhered mortar and calcium carbonate ($CaCO_3$) precipitation on the surface of RA (Kazmi et al., 2019). Although all methods used to remove adhered mortar on RA will improve the performance vastly, however, it also increases the energy consumption and CO_2 emission.

Among all these treating methods, this experimental study is focused on removing adhered mortar using chemicals. One study found out that utilization of acetic acid in removing the adhered mortar is assessed to be the best technique (Kazmi et al., 2019). Acetic acid weakens the adhered mortar of RA by reacting with calcium hydroxide (C-H), calcium silicate hydrate (C-S-H), and $CaCO_3$. In contrast to other acid treatments, this approach is known to be less costly, safer, and cleaner. Furthermore, the waste produced through acid treating could be used as an admixture in concrete.

Cement slurry coating is also a treating method used to enhance the surface properties of the RA. According to the research, maximum strength of concrete could be achieved for cement slurry coated RA by reducing the water ratio from 0.49 to 0.41 (Shrinath et al., 2016). An evaluation is done on both treating methods based on the mechanical properties of RAC to determine the efficiency of each method.

1.2 Problem Statement

Sustainable growth has become a major concern in the construction industry, to secure our planet's future. Each year, thousands of tonnes of CDW are generated, which will inevitably end up in landfills (Masood et al., 2001). Therefore, the CDW must be recycled and reused in construction to reduce requirement for landfilling, preserve natural resources and reduce consumption of raw materials.

To achieve this goal, a new building material is implemented in the industry which is called RA. In general, RA has lower performance compared to NA. The major problem of promoting RACs for practice is their inferior properties when compared with those of normal aggregate concrete (NAC). Due to the adhered mortar on the RA, RAC shows many undesirable properties when compared to NAC such as low compressive, tensile, and flexural strength, high water absorption and porosity of RAC. Therefore, a replacement ratio of 20 – 35% is being restricted in the construction industry in China (Gao et al., 2020). However, utilization of RA in construction industry of Malaysia is considered as a new technology. Thus, this experimental study will focus on the mechanical behaviour of RAC and proposed a suitable proportion of replacement of RA in the mix composition.

Treatment on the RA should be carried out before being used to produce RAC. Several treatment approaches have been suggested, but two have been selected explicitly due to their efficacy which are acetic acid treating and cement slurry wrapping (Wang et al., 2017; Bai et al., 2020). A comparative study will be carried out to identify the efficiency of both treating methods based on the mechanical properties of the resulting concrete produced using both types of RA.

1.3 Objectives

The objectives of this research are as follows:

1. To assess the effect of recycled aggregate as partial replacement of normal aggregate on properties of concrete.
2. To evaluate the efficiency of different treatment methods of recycled aggregates based on the effect on properties of concrete.
3. To determine the optimum replacement ratio of acid treated recycled aggregate in concrete.

1.4 Scope of Work

The scope of this study included the determination of mechanical properties of recycled aggregates treated by different methods that were used to replace coarse natural aggregate in the mix design. A comparison study was carried out for untreated RA, chemically treated RA and cement slurry coated RA at 20% replacement ratio to evaluate the efficiency of the treating method based on the mechanical properties of the concrete. The produced RAC were evaluated based on splitting tensile test, compressive test, flexural test, and ultrasonic pulse velocity test. As such, the effectiveness of the treating methods used could be determined. Whereas to obtain optimum replacement ratio for the chemically treated RA, four batches of chemically treated RA with different replacement ratios of coarse aggregate (20%, 25%, 30%, 35%) were used to produce RAC.

1.5 Dissertation Outline

This dissertation consists of further four chapters and is organised as follows.

Chapter 1: Introduction

This chapter describes the general overview of the research which provides a foundation and background to the subject along with problem statement and scope of the study.

Chapter 2: Literature Review

This chapter covers the previous research work on recycled aggregate concrete and their mechanical properties. Furthermore, a study of the efficiency of different treating method on the recycled aggregate is highlighted.

Chapter 3: Methodology

This chapter describes the outline of the research work. Each procedure to derive the research program is explained accordingly. In addition, methodology of study and the technique used in the specimen testing are addressed in this chapter.

Chapter 4: Results and Discussion

The results and data obtained from the tests performed on the specimens are analysed and discussed in this chapter. The results are analysed and illustrated in the form of tables as well as graphs for comparison and interpretation to facilitate discussion.

Chapter 5: Conclusions and Recommendations

This chapter summarizes the key results and reviews the study objectives. Suggestions for future work are also presented.

CHAPTER 2

Literature Review

2.1 Introduction

Concrete, as the most commonly used building material, provides high strength and durability to a structure. However, it has two main negative environmental effects: it leads to greenhouse emissions during production and raw material exploitation (Wang et al., 2017). The need to resolve environmental problems is a point of concern today, as we use a vast volume of natural resources to manufacture building materials such as concrete. The concrete industry uses a substantial volume of natural resources, resulting in major environmental and energy losses, as it consumes 50% of raw materials from nature, 40% of total energy, and produces 50% of all wastes (Oikonomou, 2005). Large volumes of solid wastes are produced worldwide because of the construction of new buildings and the demolition of old ones. Therefore, many countries have started repurposing renovation and demolition wastes as new building materials. This is one of the most important goals in terms of environmentally friendly building (Parshotam, 2019). Recycling CDW to generate substitute of aggregates for concretes is a viable strategy for mitigating these two negative environmental impacts. However, due to their poor qualities as opposed to Natural Aggregates (NA), the RAC is predominantly used in low-value added purposes such as roadbed materials (Wang et al., 2017). For the ongoing inquiry, a comprehensive literature review was undertaken with an emphasis on concrete manufactured from recycled materials for long-term sustainability. The study uses a variety of treatment approaches for recycled aggregate in the production of RAC concrete to evaluate their efficiency based on their mechanical properties.

2.2 History and Background of Recycled Aggregate (RA)

Using CDW material as aggregates in fresh concrete was initially introduced and used during World War II, when massive amounts of rubble and waste were created as a result of bombings in cities, particularly in the United Kingdom and Germany (Nixon, 1978). However, for today's society, using CDW is considered as vital in the overall attempt to achieve sustainable growth due to the exploitation of natural resources. The concept of concrete recycling is normally linked with three factors: 1) rise in the number of buildings being demolished after they have outlived their usefulness, 2) the demand for new structures, and 3) the destruction of structures due to natural disasters such as earthquakes (Oikonomou, 2005). By using demolition waste as recycled aggregate, it could be beneficial to both environmental and economical aspect (Vaishnavi Devi et al., 2021). The RA is often used as road base or subbase material in most country since RA is considered less valuable and poorer quality compared with natural aggregate (Sataloff et al., 2019). RA are normally produced by reducing the concrete debris into smaller pieces through multiple crushing stages (Akbarnezhad et al., 2011). Meanwhile, the RAC was discovered to have greater water absorption, lesser compressive strength, equivalent freeze/thaw resistance, and lower dry shrinkage than Natural Aggregate Concrete (NAC) (Wang et al., 2021).

2.3 Construction and Demolition Wastes (CDW)

CDW is often described as a material that is inextricably produced as a result of construction and demolition (C&D) activities and must be properly managed to avoid negative economic, environmental, and social consequences (Kabirifar et al., 2020). The CDW is one of the most abundant forms of waste generated worldwide, it is often being sent to landfills due to the lack of common definition of its constituents. CDW should be well-managed; otherwise, the needlessly created CDW may have harmful social, economic, and environmental implications (Kabirifar et al., 2020). Generally, CDW comprise two categories which are construction waste and demolition waste.

Construction waste is described as relatively clean, heterogeneous building materials that are created because of various construction activities. Plan sources, sourcing sources, material processing sources, service sources, residual sources, and other sources are all possible sources of producing building waste. The quantity and nature of construction waste produced by any given project, on the other hand, will vary depending on the project's circumstances and materials (Vaishnavi Devi et al., 2021). The qualities of recycled aggregate are significantly reliant on the C&D waste plant's production method and the CDW source (Martín-Morales et al., 2011). The development and execution of a systematic and realistic sustainable waste management plan that controls the volume and forms of construction waste is one potential solution to this issue (Umar et al., 2021).

Demolition wastes are usually demolished materials such as aggregate, concrete, wood, paper, metal, and glass that are contaminated with paints, adhesive, and soil. This form of waste is usually produced from building demolishing work, or by natural disasters such as earthquakes and floods (Vaishnavi Devi et al., 2021).

2.4 Recycled Aggregate Concrete (RAC)

Recycled Aggregate Concrete are usually produced using a single source of RA mixed with natural aggregates, cement and other additives (Thomas et al., 2016). Even though adopting RA in construction can save resources and reduce carbon footprint, but several previous studies have shown that the performance of RAC is often weakened after adoption. While reusing RA saves money by reducing resource use, it has drawbacks such as poor interfacial behaviour between aggregate and cement paste, higher cement mortar portions attached, and lower consistency. Figure 2.1 depicts the microscopic view of the RA in RAC.

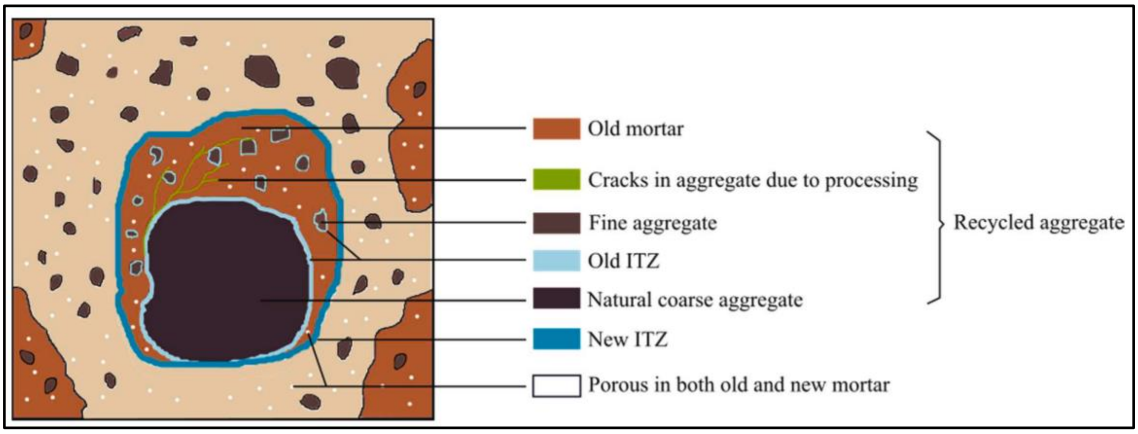

Figure 2.1: Illustration of RA in RAC (Wang et al., 2021)

Since cement grains come in a variety of sizes and shapes, they are unable to coat the aggregate surface perfectly. Voids will be created adjacent to the aggregate and filled by small molecules such as water and air. The adjacent zone around the aggregate is called the interfacial transition zone (ITZ). As a result, the load bearing ability of ITZ in RAC is always lower than that of NAC due to the increased number of tiny grains and voids (Wang et al., 2021). Most RAC consist of two ITZ which are, an old ITZ between RA and adhered mortar, and a new ITZ between RA and new mortar. Therefore, RAC usually exhibits lower mechanical properties compared to NAC. Table 2.1 provides a summary of the reduction in mechanical properties of RAC after adopting RA in concrete at different replacement ratio in a review by Tam et al. (2007).

Table 2.1: Summary of previous research on RAC (Tam et al., 2007)

Sources	Replacement ratio	Compressive strength	Flexural strength	Modulus of Elasticity
Acker (1998)	100% replacement of coarse recycled aggregate (CRA)	17.2% lower	20% lower	23% lower
Ahmed & Struble (1995)	100% replacement of CRA	33% lower	16% lower (at 14 days)	
Bretschneider (2004)	100% replacement of CRA		8.1% lower	11.9% lower
	75% replacement of CRA		8.1% lower	4.0% lower
	50% replacement of CRA		8.1% lower	5,8% lower
Frondistou-Yannas (1977)	100% replacement of CRA	4-14% lower		40% lower
Grubl et al. (2004)	100% replacement of CRA			28.3% lower
	75% replacement of CRA			21.9% lower
	50% replacement of CRA			23.3% lower
	25% replacement of CRA			13.6% lower
Hansen and Marga (1988)	100% replacement of CRA	30% lower		
Ikeda et al. (1988)	100% replacement of CRA	15-40% lower		30-50% lower

Kakizaki et al. (1988)	100% replacement of CRA and fine recycled aggregate (FRA)	32% lower		40% lower
Masood et al.(2001)	10% replacement of FRA	20% lower	4.2% lower	32.4% lower
	20% replacement of FRA	22.6% lower	7.3% lower	22.7% lower
	30% replacement of FRA	25.5% lower	10.4% lower	20.2% lower
Nishibayashi and Yamura (1988)	100% replacement of CRA	15-30% lower		15% lower
Roos (2003)	100% replacement of CRA	34% lower		36.4% lower
Teranishi et al. (1998)	50% replacement of CRA	57.8% lower		30.5% lower
Topcu (1997)	30% replacement of CRA	31.8% lower		
	50% replacement of CRA	45.5% lower		
	70% replacement of CRA	54.5% lower		
	100% replacement of CRA	86.4% lower		

2.5 Production of Recycled Aggregate Concrete (RAC)

One popular method for producing environmentally sustainable concrete is by crushing CDW to create RA for the production of fresh concrete. This method conserves natural resources and reduces the disposal of construction wastes in landfills. The current approach of producing RA only adjusts the aggregate size rather than removing the attached mortar. Therefore, the production plant nowadays only comprises of a jaw crusher and vibrating screen. Figures 2.2 and 2.3 depict a manufacturing plant for recycling CDW, it only selects aggregate by altering the open set for crusher and scale them according to particle size (Eguchi et al., 2007). Figure 2.4 shows the step-by-step production processes for the RA.

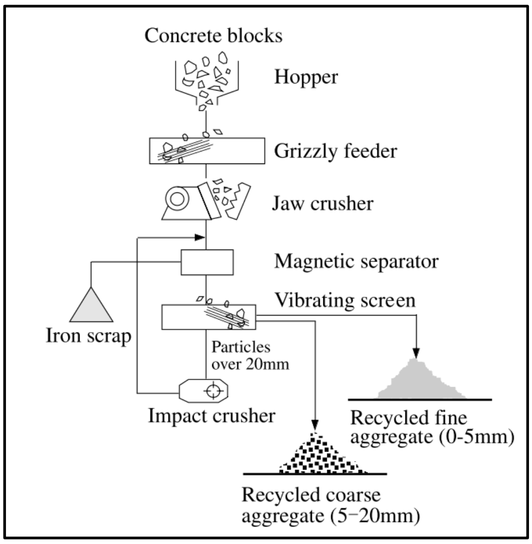

Figure 2.2: Flow chart of recycled aggregate production (Eguchi et al., 2007)

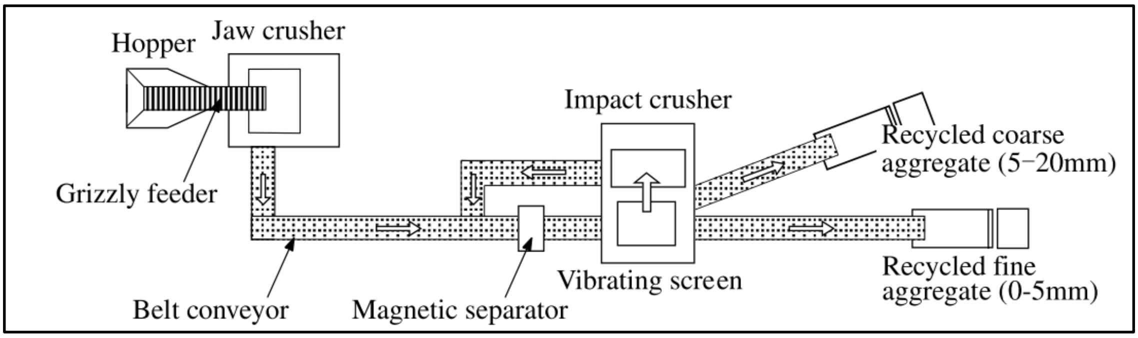

Figure 2.3: Production plant for recycled aggregate (Eguchi et al., 2007)

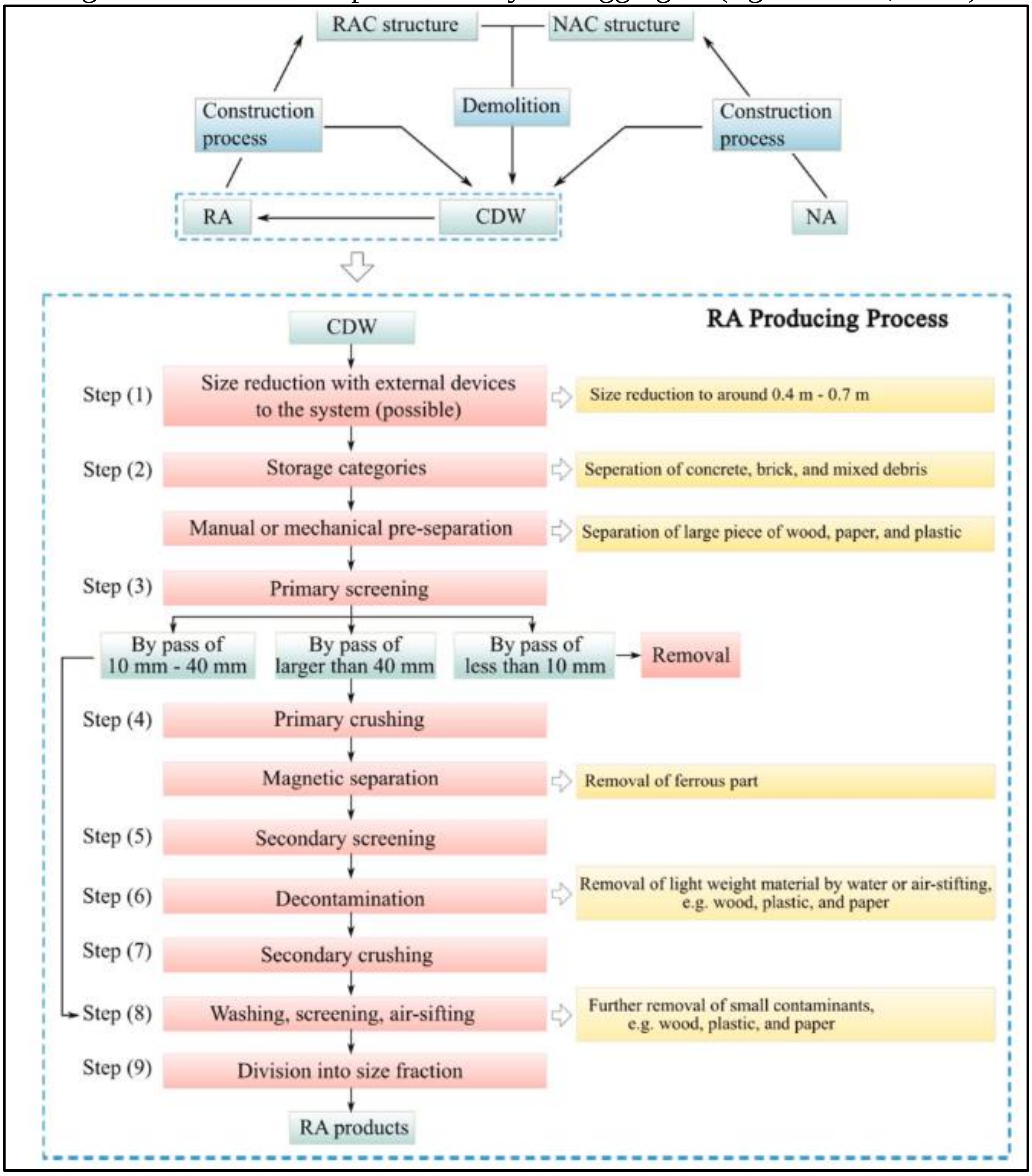

Figure 2.4: Producing process of RA (Hansen, 1986; Pellegrino and Faleschini, 2016)

CDW recycling facilities are divided into two categories: stationary and mobile. For stationary facilities, CDW must be transported and processed off-site, but it has higher handling capacity and generates higher-quality RA. On the other hand, mobile facility can process CDW on-site to produce RA to be used in new construction on-site without additional transportation (Wang et al., 2021). Referring to Figure 2.4, there are a total of nine steps to produce RA from CDW, which include (1) size reduction by reducing large pieces into smaller debris, (2) pre-separation for higher efficiency of the process, (3) primary screening to remove smaller particles such as soil and gypsum, (4) primary crushing and magnetic separation to reduce the size of RA, (5) secondary screening to further remove soil, gypsum and dust, (6) decontamination by washing off light weight component, (7) secondary crushing to scale down the size of debris, (8) washing, screening, air-sifting to remove remaining contaminants and (9) dividing the aggregates into various size fractions. In primary screening, the by-pass between 10 mm and 40 mm may be shifted to (8) directly whereas the by-pass larger than 40 mm should continue with the process in (4). Finally, those passing 10mm could be removed as they are mostly soil and gypsum (Wang et al., 2021).

2.6 Characteristics of Recycled Aggregate Concrete (RAC)

When compared with natural aggregate (NA), the presence of adhered old mortar causes RA to have lower density, high porosity, rough and irregular surface, high water absorption, high crushing value, and existence of micro-cracks, among other characteristics (Thomas et al., 2016). Generally, RAC has drawbacks such as high water absorption, shrinkage, poor mechanical properties, and reduced durability (Kazemian et al., 2019). There is consensus that the quality of cement adhered to the RA will influence the physical, mechanical, and chemical properties of the RAC. Studies have shown that the quality of recycled aggregate is commonly determined by the recycling process methods used, but the different properties of recycled aggregate are primarily determined by the water cement ratio of the pioneer concrete from which it is made. The strength of the parent concrete and the number of crushing stages had a big impact on the RAC (Parshotam, 2019).

In terms of water absorption, RA is 6 to 12 times higher compared with NA due to the adhered mortar on the aggregates. Besides, water adsorption of RA amplified with the increases in strength of the parent concrete, though this declines as the maximum aggregate size increases (Padmini et al., 2009). Due to the water adsorption properties, a greater amount of mixing water is required to achieve the desired workability. The effect is more significant if the particle size of RA is relatively smaller since the total surface area of the aggregate is subsequently higher (Parshotam, 2019).

Even though there are a few limitations on the widespread usage of RA in the construction industry due to its strength, workability, and durability, the possible application of RA has been acknowledged. As a result, various properties of RA, such as aggregate size, particle size distribution, impurity amount, porosity, absorption, stiffness, hardness, strength of parent concrete, and others, must be examined prior to its use in concrete (Parshotam, 2019).

2.6.1 Workability and Water Demand

RAC usually have lower density and greater water absorption due to the adhered mortar on the aggregate. RA will have two transition zones in RAC, the existing interface of old adhered mortar and original aggregate, as well as the new interface of old adhered mortar with new mortar. The discussion of fresh RAC is as below.

When concrete is in its early stages, variables such as the water cement ratio or the properties of the aggregates will have a significant impact on properties such as workability and wet density. Physical state of aggregate, such as surface structure, aggregate scale, and aggregate form, have often affected the workability of fresh concrete (Parshotam, 2019). Workability is a decisive factor that affect the performance of RAC.

According to the literature, the pore structure of bonded mortar causes RA to have a higher water absorption potential than raw aggregate, hence a higher water demand (Martín-Morales et al., 2011). The water absorption properties of RA will have a negative impact on the workability of the concrete. Even though it could be compensated by pre-soaking RA, however, the strength of the concrete will be afflicted (Tam et al., 2007). Besides, the water demand increases as the size of RA reduces due to the increased total surface of particles attached with mortar. As a result, it is more difficult to regulate the properties of fresh concrete, which has an effect on the strength and longevity of hardened concrete (Padmini et al., 2009). To improve the workability of the RAC, treatment of the surface of RA was introduced to seal the pores of adhered mortar on the RA, thus improve the workability of the RAC (Liang et al., 2015).

2.6.2 Density

Generally, RAC has lower density compared with NAC due to the existence of old cement paste on the RA. According to Thomas et. al (2016), despite the lower effective water/cement ratio, the densities of RAC manufactured of unsaturated recycled aggregate are lower than the control concrete. With an addition of 20% recycled aggregate, the density of RAC is approximately 5% lower than the control concrete (Thomas et al., 2016).

2.6.3 Compressive Strength

Compressive strength is one of the most significant characteristics which determines the properties of concrete. Review shows that an increase in RA replacement will decrease the compressive strength of the concrete. According to Etxeberria et al. (2007), with the same amount of cement used and w/c ratio, concrete with a 100% replacement ratio of CRA will have 20 to 25% lower compressive strength than normal aggregate concrete at 28 days. To produce high compressive strength RAC with 100% replacement of CRA, a huge amount of cement is required, therefore, it is not economical. The lower strength of RAC is due to the adhered mortar attached to the RA that weaken the bond between fresh mortar paste and RA. However, with a 25% replacement ratio of RA, concrete with medium compressive strength in the range of 30 to 45MPa could be produced with the same quantity of cement and w/c ratio as NAC to achieve the same mechanical properties. Study shows that to achieve the same compressive strength at 28 days, medium compressive strength concrete with 50% or 100% replacement in coarse aggregates needs a 4 to 10% lower effective w/c ratio and 5 to 10% more cement than standard concrete (Parshotam, 2019). Another research shows that the compressive strength of high-performance concrete (70 MPa) and normal strength concrete (35 MPa) with 50% replacement in RA, both dropped at 2.8% in strength. With a 100% replacement ratio of RA, the compressive strength of the concrete was decreased by 8.34% for type 35 MPa and 14.29% for type 70 MPa, compared to the control concrete (Mohammed et al., 2017).

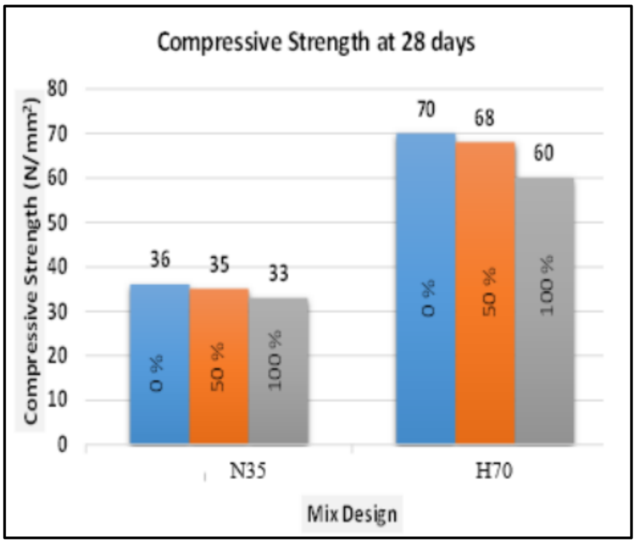

Figure 2.5: Compressive strength of concrete at 28 days (Mohammed et al., 2017)

Similarly, Kou and Poon (2012) also reported that compressive strength of RAC at 28 days decreased due to the adhered mortar on the recycled aggregates and also the higher initial free water content in the concrete mixture resulting from the higher water absorption of recycled aggregate. However, there are a few cases in which the incorporation of recycled aggregate can increase the compressive strength of concrete which is responsible to the good control of the grading of recycled aggregates (Bai et al., 2020). Possibly due to the improved bond strength between the adhered mortar and the new cement paste can be strengthened in the Interfacial Transition Zone (ITZ).

2.6.4 Flexural Strength

The measure of flexural strength could be foreseen from the compressive strength of the concrete, but this does not apply to RAC. Some researchers revealed that as the proportion of RA in concrete increases, the flexural strength of the concrete decreases (Padmini et al., 2009; Parshotam, 2019). Kang et al. (2012) showed that the replacement of RA in concrete has a significant effect on the flexural strength of the concrete. The flexural strength was 13% lower when the CRA replacement proportion was 15–50%. Moreover, some different literatures discovered that the flexural strength of RAC could decrease up to 10%. In the test carried out by Mohammed et al. (2017), the flexural strength for normal strength concrete (35 MPa) at 28 days with 50% and 100% RA replacement is reduced by 2.3% and 11.4%, respectively. In addition, the reduction in flexural strength for high strength concrete (70 MPa) is at 4.8% and 17.8% for specimens with 50% and 100% RA replacement, respectively. Table 2.2 shows the summary of the test result.

Table 2.2: Flexural strength for concrete at 28 days (Mohammed et al., 2017).

Specimen	Code	Flexural Strength (MPa) at 28 days
N35	35 N.C	4.4
	50% R35	4.3
	100% R35	3.9
H70	70 N.C	6.2
	50% R70	5.9
	100% R70	5.1

As compared to natural aggregate concrete, the flexural strength of fully recycled aggregate concrete deteriorated due to the formation of a weaker ITZ in recycled aggregate concrete. According to Parshotam (2019), the tensile strength loss could be compensated by using nano silica, which improves the ITZ of CRA by filing the pores present in it and improving the bond between the cement paste and aggregates.

2.6.5 Splitting Tensile Strength

Splitting tensile strength is one of the most tested characteristics to evaluate concrete. According to some of the previous studies, RAC has splitting tensile strength comparable to conventional concrete. Some even exhibit better tensile strength compared with natural aggregate concrete when the replacement ratio was as high as 30% (Bai et al., 2020). According to Dilbas et al. (2014), it shows that the strength of the concrete with 5% replacement ratio of RA has higher tensile strength compared with normal concrete. As described by Etxeberria et al. (2007), recycled aggregate has better tensile strength compared with normal concrete, except for 100% replacement. This is due to the improvement in absorption of the mortar correlated with the recycled aggregate and the viable ITZ, which exhibits a better bond between aggregate and the mortar matrix in the transition zone. On the other hand, some research found that replacing RA in concrete will reduce the splitting strength of the concrete (Mohammed et al., 2017). The splitting tensile strength of his research is exhibited in the below.

Table 2.3 Split tensile strength for concrete at 28 days (Mohammed et al., 2017).

Specimen	Code	Split Tensile Strength (MPa) at 28 days
N35	35 N.C	3.5
	50% R35	3.4
	100% R35	3.2
H70	70 N.C	5.5
	50% R70	5.4
	100% R70	4.6

Bai et al. (2020) also revelaed that when 25%, 50%, and 100% RA replacement ratios were used, the splitting tensile strength of RAC was 6%, 10%, and 40% lower than that of the NAC, respectively.

2.7 Treatment Method of Recycled Aggregate (RA)

The amount of attached mortar on the aggregate is the primary distinction between natural aggregate and RA. Removing the adhered mortar from the RA is a feasible way to increase the performance of RAC. When old concrete is crushed, some of the original cement mortar remains attached to the RA, forming a fragile and porous layer (Tam et al., 2007). The RA characteristics are directly affected by the porosity of the cement mortar attached such as lower strength and higher water absorption. Few treating methods have been developed to remove the adhered mortar from RA including mechanical rubbing, wrapping method, thermal process and chemical process (Tam et al., 2007; Akbarnezhad et al., 2011).

Mechanical rubbing is a treatment method that removes the residual mortar on the RA by exerting physical force to the RA. According to Xuan et al.(2016), this method may greatly minimise water absorption and enhance the compressive strength of concrete, but the disadvantages of these approaches include the high energy input needed and the resulting rise in recycled fines output from 40% to 70%. In fact, FRA with particle sizes less than 5 mm have even worse properties and must be disposed in landfills.

For cement slurry wrapping method, the cement slurry used could be made from single or multiple components, such as cement, fly ash, mineral powder, and silica fume, to coat the recycled aggregate. Recycled aggregates are coated with pozzolanic materials to improve the working performance of the RAC. Hydration products of pozzolanic materials are mostly utilised to fill the pores in old recycled aggregate mortar, hence strengthening the recycled aggregate (Wang et al., 2020). However, the mechanical properties were not much enhanced and the process is time consuming, costly and inconvenient (Xuan et al., 2016).

In thermal process, RA is heated up to a high temperature to dehydrate the cement hydration products. This method will greatly weaken the adhered mortar, allowing it to be mechanically removed from the RA. For this method, not only does it consume a lot of thermal energy, but it also emits excess carbon dioxide (Wang et al., 2017).

Instead of heating up the RA, the chemical process weakens the adhered cement mortar on RA by using a low-concentration acid (hydrochloric acid, sulfuric acid, and phosphoric acid) (Tam et al., 2007). In this process, RA are immersed in a solution of low-concentration acid to dissolve any hydration product of cement. This procedure will strip any loose and cracked mortar from RA, resulting in a decrease of up to 28% of water absorption and greatly improved the mechanical properties of RAC produced with acid treated RA. Furthermore, according to Kazmi et al. (2019), waste generated by acetic acid treatment can be employed as a concrete additive. However, strong acids used in this method, not only may endanger the workers wellbeing if being used practically, but also contribute harmful ion to the RA such as Chloride ion (Cl^-) and Sulphate ion (SO_4^{2-}) (Wang et al., 2017).

2.8 Sustainability of Recycled Aggregate Concrete (RAC)

The surge in construction activity has culminated in a larger increase in demand of construction materials. The CDW pollution has been ignited due to this rapid modernization and industrialization. In general, utilizing supplementary cementitious materials improves the concrete industry's sustainability by reducing the usage of cement in construction. Other than that, the use of RA in replace of raw aggregates is one of the most popular options for improving sustainability in concrete manufacturing (Pellegrino and Faleschini, 2016). Effective techniques that could improve the characteristics of RAC could expand the application of RA in actual construction project hence achieving a more sustainable development. These techniques could be classified into three categories: (1) enhancing the properties of RAC by introducing effective mixing method, (2) adding admixtures to improve the RAC performance, and (3) remove the adhered mortar on RA to improve the quality of aggregate. Even though these studies are extremely useful and have yielded excellent results that can enhance the property of RAC, yet they cannot be widely implemented in actual projects as these methods typically include complicated processess that last a few days or require some expansive and specialized strengthening materials and equipment. Therefore, engineers in the construction industry are reluctant to use these complex, time-consuming, and uneconomical techniques (Mi et al., 2020). However, carbonation in concrete is one of the major concerns in the construction industry, hence, improving the carbonation resistance in RAC could promote the utilization of RA in the industry. Some researchers (Silva et al., 2015) show that the carbonation of RAC could be worse than NAC if the original concrete (OC) selected is less effective than the intended RAC. As a result, increase the carbonation resistance of RAC by choosing a suitable OC and then preparing RAC, thus improving the sustainability of RAC. Hopefully, engineers in concrete industries would be able to choose the proper OC to prepare RAC based on slump and strength requirements, thus bridging the gap between construction companies and concrete manufacturers to increase the application of RAC in actual projects, thus efficiently recycle waste concrete in CDW (Mi et al., 2020).

2.9 Summary

This chapter presents the review of literature and identifying the issues of physical and mechanical properties of concrete when partially replace recycled aggregate. Research gap was listed as below:

1. Researchers often uses 50% and 100% replacement for RAC studies. However, 25% partial replacement of RA was not commonly done to assess the properties of concrete.
2. It was identified that the properties of RA are highly dependent on the treatment methods. Detailed study of the efficiency of different treatment method on coarse recycled aggregate is required.
3. In most of the cases, the research emphasizes on treatment using strong acid which is more effective but produces hazardous products rather than treatment by using weaker acid which is safer to both human and the environment. Therefore, optimal mixing proportion for weak acid treated recycled aggregate has not been formulated.