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A comprehensive assessment of concrete with recycled coarse aggregate treated by a combination of heating, grinding, and acid-soaking process

Una evaluación integral del concreto con agregado grueso reciclado tratado mediante una combinación de calentamiento, trituración y remojo en ácido

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Abstract

Waste generated after a concrete construction demolition causes environmental problems. Utilization of recycled aggregates extracted from concrete waste has been recommended to overcome these problems. Aggregates occupy about 70-80% of concrete volume; therefore, using recycled aggregate from waste concrete can potentially prevent the landfill problem. So far, the conventional recycling method is processed by crushing the concrete rubble into smaller sizes according to fine and coarse aggregate sizes. However, the product still needs to achieve an adequate quality recycled aggregate. Several methods have been attempted to obtain better quality; though, they demand a reasonably high cost. Recycled aggregates produced from a combination of thermal, mechanical, and chemical processes are proposed in this study. This production process is relatively easy, especially for developing countries. In addition, the results obtained significantly improve the quality of recycled aggregates compared to the conventional method. This paper comprehensively discusses the recycled aggregate produced by a combination of thermal, mechanical, and chemical processes. The reviews involve the recycled aggregate's physical properties, the concrete's mechanical and microstructural properties, and the production costs of concrete made from these recycled aggregates. As a comparison above, concrete made from natural aggregates is also analyzed.

Keywords: Recycled coarse aggregate; heating-grinding-acid process; aggregate physical properties; concrete mechanical properties; concrete microstructures; economic analysis.

Resumen

Los residuos generados por la demolición de una construcción de hormigón provocan problemas medioambientales. Para superar esta situación, se ha recomendado utilizar los áridos reciclados extraídos de los residuos de hormigón. Los agregados representan del 70 al 80% del volumen del concreto; por lo tanto, el uso de agregados reciclados a partir de desechos de concreto tiene el potencial de reducir el uso de botaderos. Actualmente, el método de reciclaje convencional tritura y reduce los escombros de hormigón según el tamaño de los agregados finos y gruesos. Sin embargo, este producto aún debe convertirse en un árido reciclado de calidad adecuada. Aunque existen varios métodos para obtener una mejor calidad, el costo es razonablemente alto. Este estudio propone producir agregados reciclados combinando procesos térmicos, mecánicos y químicos. Un proceso relativamente fácil, especialmente para países en desarrollo. El cuál mejora significativamente, la calidad de los áridos reciclados respecto al método convencional. El presente artículo discute exhaustivamente sobre el agregado reciclado producido mediante una combinación de procesos térmicos, mecánicos y químicos. Evaluándose las propiedades físicas del agregado reciclado, las propiedades mecánicas y microestructurales del concreto y el costo de producción del concreto elaborado a partir de estos agregados reciclados. Adicionalmente este análisis se contrasta con hormigón elaborado a partir de áridos naturales.

Keywords: Agregado grueso reciclado; proceso de calentamiento-molienda-ácido; propiedades físicas del agregado; propiedades mecánicas del hormigón; microestructuras de hormigón; análisis económico.

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1. Introduction

Concrete has been broadly used as a building material besides steel and wood. In general, concrete is obtained by mixing Portland cement, water, and aggregate. Special types of concrete require additives such as chemical additives, mineral additives, or fiber. There are several reasons why concrete structures must be demolished, for instance, having exceeded their service life, changing the function of the building, or being damaged. Demolition of a concrete construction might result in large quantities of waste, and it can threaten the environment due to inevitable landfills shortly (Azúa et al., 2019); (Kabirifar et al., 2020); (Villoria-Sáez et al., 2020). In addition, the problem of continuously mining natural aggregates to meet the increasing construction needs lately has also become a global concern (Pacheco-Torgal, 2020). The application of recycled aggregate has become an answer to the problems raised. Thus, studies on recycled aggregate continue to develop to meet the requirements to be used progressively in replacing natural aggregates in construction (Assi et al., 2018); (Chen et al., 2019); (Kenai, 2018); (Martínez-Lage et al., 2020).

The history of using recycled aggregate from concrete waste began with only cutting the concrete lump into required sizes to be applied as fillers in concrete mixtures. However, because the compressive strength of the concrete produced is much lower than concrete made from natural aggregate (Berredjem et al., 2020); (Etxeberria et al., 2007); (Pacheco et al., 2019); (Xiao et al., 2005); therefore, the application is limited such as a road base material.

Studies are progressing to improve recycled aggregate quality to achieve better quality concrete. Efforts have been conducted both by increasing the recycled aggregate quality (Katz, 2004); (Pepe et al., 2014a); (Santha Kumar and Minocha, 2018); (Tam et al., 2007a) and by increasing the strength of the old mortar in the interfacial transition zone (Djerbi, 2018); (Mistri et al., 2020).

Germany and Japan developed a high-shock energy system to produce high-quality recycled aggregate from concrete waste. The technique enables to dismantling of the cement paste, which originated from the old mortar. Therefore, recycled aggregate surfaces are free from the attached remaining old material and visually appear like a new aggregate. In addition, the physical properties of the recycled aggregate are similar to those of new fresh aggregate. Likewise, the concrete manufactured using recycled aggregate achieves mechanical properties as good as those produced from fresh, natural aggregate for the same mixture composition. However, high-voltage systems like pulse power are difficult to apply in some countries (Bluhm, 2006); (Kencanawati et al., 2013); (Narahara et al., 2007).

The most suitable method for extracting aggregate from the waste is necessary to produce a better-quality recycled coarse aggregate (RCA). The application of thermal, mechanical, and chemical methods for the treatment of waste concrete to achieve the same goal of increasing the quality of RCA has been proposed. The process is considerably easy and provides such potential results (Kencanawati et al., 2015), (Kencanawati et al., 2017), (Kencanawati et al., 2021). However, studies are still being conducted to confirm this recycled aggregate potential further. This paper presents a comprehensive analysis including the physical properties of RCA, mechanical properties of RCA concrete, microstructures of RCA concrete, and economic aspects of RCA production. The results provide broader quantitative or qualitative details in considering the use of recycled aggregates for concrete manufacturing.

2. Experiment and method

2.1 RCA Production

The first method applies the thermal (heating) method and is continued by a mechanical (grinding) process. The product is called heating-grinding recycled coarse aggregate (HG RCA). Concrete rubble was collected from a laboratory testing waste and those which were categorized as normal strength concrete. The concrete lump was prepared with a size of around 10-20 cm in diameter. The concrete lump was heated at a temperature of up to 100 degrees Celsius for 24 hours. After the first process, the heated concrete waste was ground for a number of 500 cycling processes. To separate the attached mortar, the cycling process was improved from 500 cycles (Kencanawati et al., 2017), to 600 cycles to be more effective in delaminating the attached mortar.

There is an additional process for the second type of RCA, which was immersed in sulfuric acid (H_2SO_4) with a concentration of 0.1 mol for 24 hours after thermal and mechanical processes. This RCA is called heating-grinding-acid (HGA) RCA. This additional process provided continuous old mortar detachment (Kencanawati et al., 2015); (Tam et al., 2007b). Cleaning the residual chemical content with fresh water was the final stage of this method. The production of RCA is illustrated in (Figure 1). To examine the quality of the RCA, the sieve analysis, the density, the fineness modulus, and the water absorption analysis were conducted according to the standard (ASTM C33 / C33M-18, 2018).

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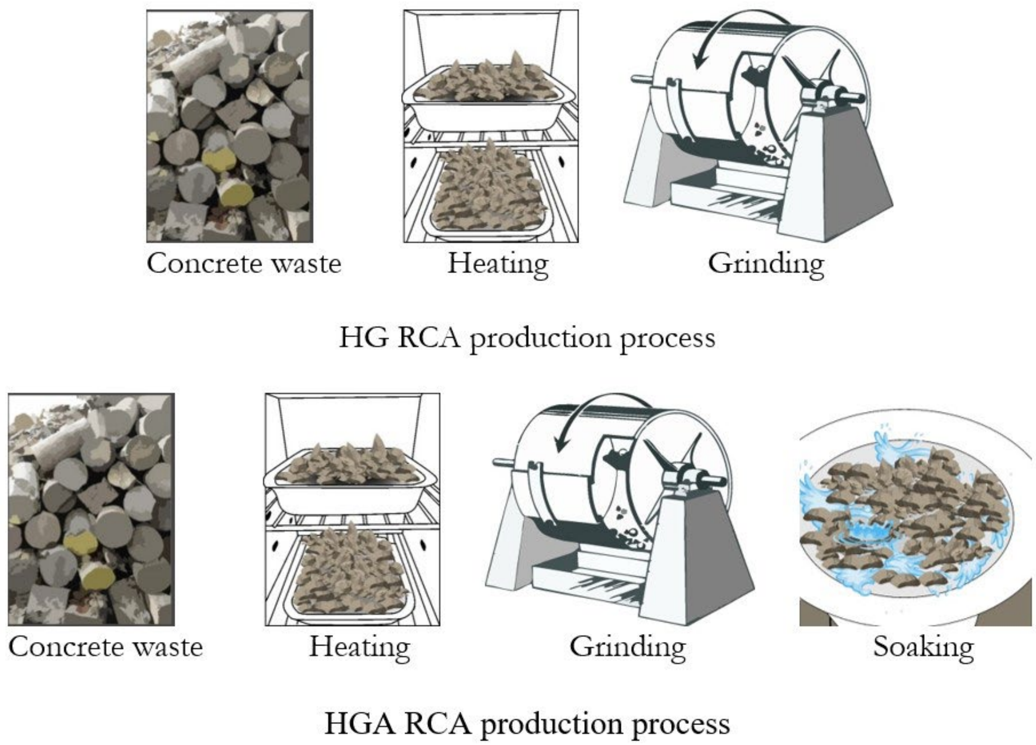

Figure 1. Recycling process.

2.2 Concrete Production

New concrete was produced using HG and HGA recycled aggregate. Concretes made from natural coarse aggregate (NCA) were also manufactured to compare the properties. The natural coarse aggregate was the limestone crushed aggregate with a maximum nominal diameter of 19 mm. All the concrete types consisted of fine natural aggregate with a maximum nominal diameter of 4.75 mm. Similar to RCA, natural crushed coarse aggregate (NCA) and natural fine aggregate physical properties were evaluated under the testing standard (ASTM C33 / C33M-18, 2018).

(Table 1) shows the mixture proportion of the concretes. The water-cement ratio was 48% and was kept among the concrete mixtures. The binder was the first type of Portland cement. The concrete materials mixing procedure begins by entering dry materials, namely coarse aggregate, fine aggregate, and cement, into the concrete mixer. These ingredients were rotated and mixed properly, and then the water was added to the mixture. All ingredients were mixed for 2 minutes. Slump testing was conducted to evaluate the effect of attached old mortar of recycled coarse aggregates on concrete workability. The specimens for the compression test were cylinders concrete standard (diameter: 150 mm and height: 300 mm). After being hardened, the concretes were immersed in water for 28 days of curing times. Then, the specimens were loaded using a compression testing machine until failure..

Table 1. Concrete mixture proportion.

Specimen types	Proportion (kg/m^3)			
	Cement	Water	Fine aggregate	Coarse aggregate
NCA concrete	410	205	694	1041
HG RCA concrete	410	205	680	1020
HGA RCA concrete	410	205	682	1023

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3. Result and discussion

3.1 RCA visual apparent

(Figure 2) presents the visual appearance of NCA, HG RCA, and HGA RCA. At a glance, the surface of the recycled aggregates of both the HG RCA and HGA RCA types appears to be free of mortar from old concrete. Although the old mortar has separated from the aggregate surface, the figures show the difference in RCA's old mortar coverage surface area. The surface area of HGA RCA is slightly cleaner and darker than those of HG RCA. HG RCA appears to be more whitish surfaces due to the color of old mortar. Soaking in a chemical solution plays a role in releasing the rest of the old mortar; thus, HGA RCA has a cleaner surface than HG RCA It is evident because the attached mortar is observed at around 4% on the surface of HGA RCA; meanwhile, it is around 6% in HG RCA. Compared to NCA, as presented in the figure, the NCA surface is free from old mortar layers and shows a more continuous surface. The RCA shows a porous part with micro-cracks due to abrasion in the grinding process, which disintegrates old mortar and erodes the aggregate surfaces.

Figure 2. Appearance of NCA, HG RCA and HGA RCA.

3.2 RCA sieve analysis and fineness modulus

(Figure 3) describes the particle distribution of sieve analysis among the aggregate types. On a larger sieve size, it can be seen that NCA has a greater percentage of particles that pass the sieve than the percentage of the number of particles on the RCA. In contrast, on the smaller sieve size (4.75 mm), RCA has a greater portion of passing than NCA. The grinding process is considered to produce a smaller particle size; therefore, the aggregate distribution tends to be more in the smaller sieve size for RCA.

At each sieve size, HGA RCA tends to have a slightly larger particle of sieve passing than those of HG RCA. The cement paste content on the HG RCA surface causes the particle size to be slightly larger than the HGA particle size. Soaking with a chemical solution slightly reduces the mortar layer covering the aggregate surface. As a result, a smaller particle size is generated. Furthermore, the particle size distribution of three aggregate types meets the requirement between the upper and lower limit of grain size distribution according to the standard (ASTM C136 / C136M-19, 2019).

The assumption is confirmed by the fineness modulus value. NCA produces the lowest fineness modulus value, namely 7.27; meanwhile, HG possesses the highest fineness modulus with a value of 7.48. Although the HG RCA fineness modulus value is greater than that of the HGA RCA, the difference is not significantly noticed. This verifies that the two initial processes, thermal and mechanical, are considered effective in separating the attached mortar. Immersing the aggregate into the chemical solution simply accommodates to make it slightly cleaner. The fineness modulus values for the three types of aggregates are shown in (Figure 4). The larger fineness modulus of RCA indicates the larger particle size of RCA compared to that of NCA. However, the value is still in the range required by the standard, which is 6.5-8 (ASTM C136 / C136M-19, 2019).

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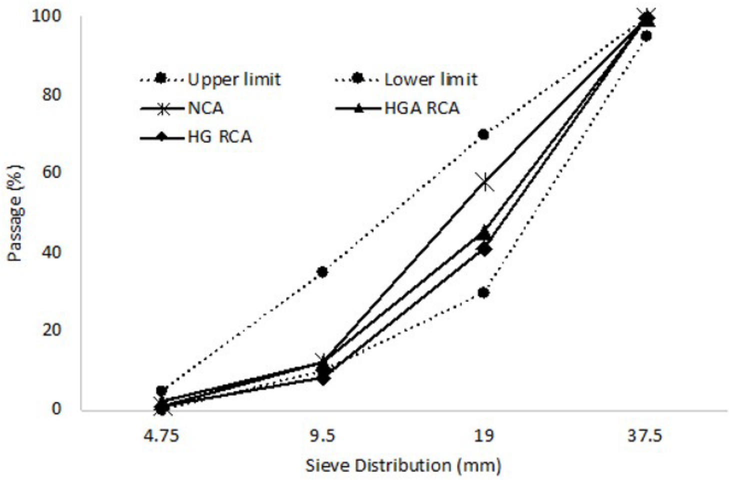

Figure 3. Particle Size distribution of coarse aggregate.

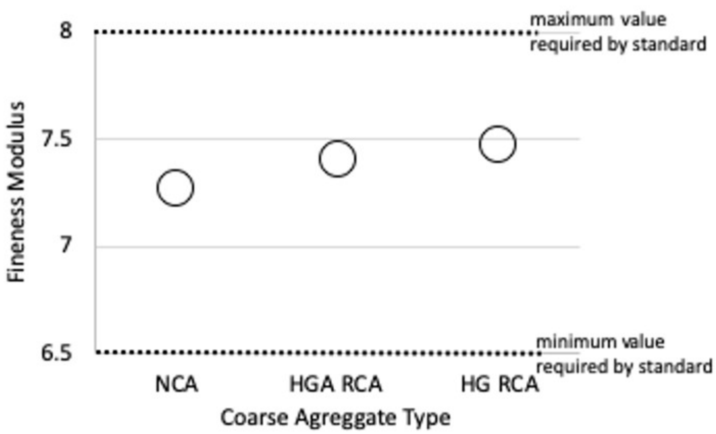

Figure 4. Fineness modulus.

3.3 RCA density and water absorption

The average density of RCA is lower than that of NCA, as illustrated in (Figure 5). HG RCA has a smaller average density of 4.1% compared to NCA. A smaller difference is achieved by HGA RCA, which is only 2.85% smaller than the NCA density. The average densities of NCA, HGA RCA, and HG RCA are 2680 kg/m^3, 2600 kg/m^3, and 2570 kg/m^3, respectively. Soaking in sulfuric acid improves the density by as much as 1.25% due to adhered mortar delamination. Even though HG RCA has the lowest density; however, the value meets the requirement for concrete aggregate because the value is more than 2400 kg/m3.

In terms of water absorption properties (Figure 6), the average water absorption of RCA is still greater than that of NCA. The average water absorption for NCA, HGA RCA, and HG RCA were 0.36, 1.98, and 2.63, respectively. The absorption ability of HG RCA water is 1.3 times that of HGA RCA water absorption. More old mortar bonds in HG RCA cause higher water absorption. The water absorption of RCA does not exceed 3% which is the maximum water absorption value required by the standard.

RCA produced by autogenous cleaning by (Pepe et al., 2014b) yielded a density value of 10% lower than the NCA density value. Furthermore, RCA produced by soaking in 0.1 mol H_2SO_4 acid solution for three days (Ismail and Ramli, 2013) showed a smaller density of 8% than NCA. The best density of RCA in this study is achieved by HGA RCA, which is lower by about 2.85% compared to NCA's density. The combination of thermal,

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mechanical, and chemical methods in this research can potentially improve the density of RCA. The comparison of the density from the three studies mentioned is presented in (Figure 7). The density of RCA is normalized to the NCA density.

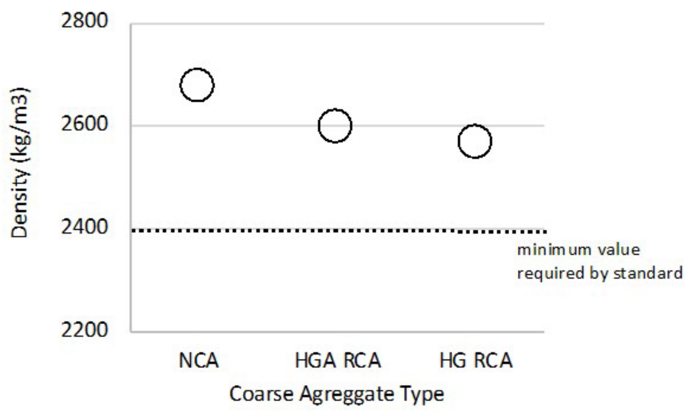

Figure 5. Density.

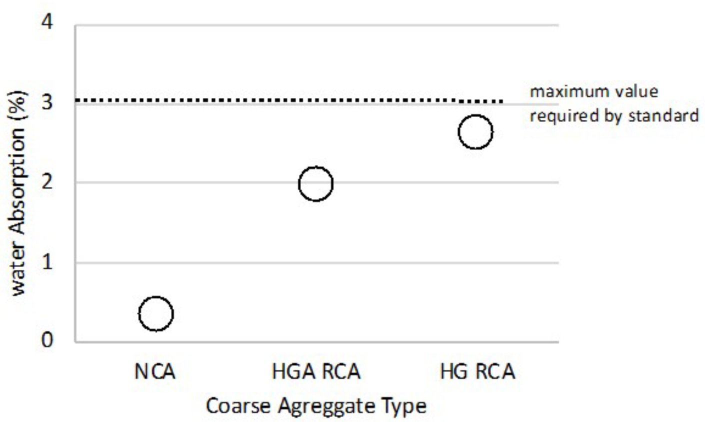

Figure 6. Water absorption.

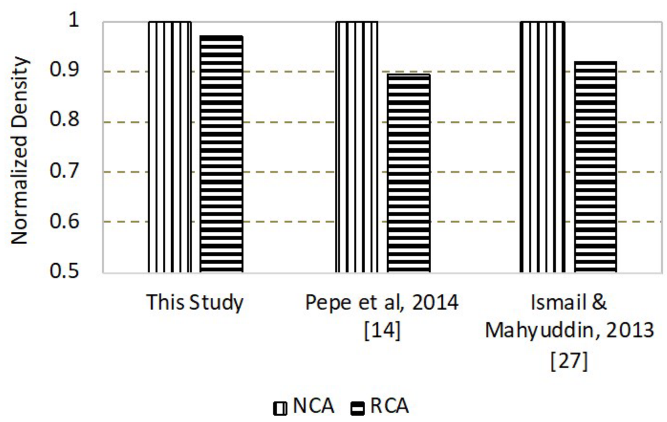

Figure 7. Comparison of RCA density.

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3.4 Fresh Concrete Properties

The slump test was conducted to evaluate the fresh properties of concrete made from RCA. Concrete slump with NCA aggregate is also conducted as a comparison. The results are shown in (Figure 8). Concrete mixes with RCA show lower slump values than concrete made from NCA. The mortar content in RCA causes the mixed water to be absorbed more on the recycled aggregate surfaces. The HG RCA concrete has the lowest slump. The highest water absorption value in HG RCA is assumed to cause the lowest slump value.

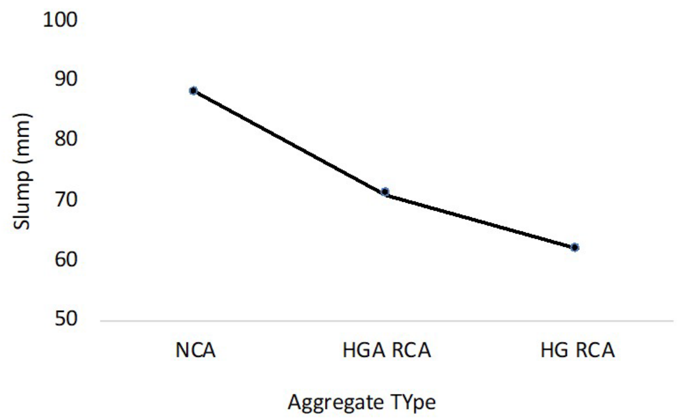

Figure 8. Fresh concrete slump.

The fresh concrete properties observed in this study are similar to the studies conducted by (Ismail and Ramli, 2013) and (Lavado et al., 2020), where the slump value of the concrete containing RCA has a lower slump value than the concrete containing NCA, as seen in (Figure 9). Besides being influenced by greater water absorption on the RCA, the lower slump value is also influenced by the shape of the aggregate, which is more irregularly found in RCA, causing a lower level of workability.

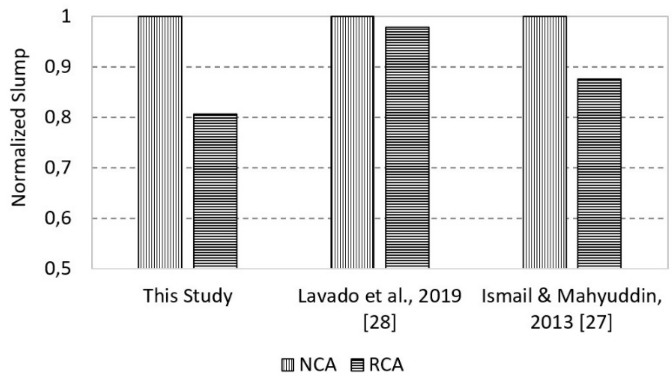

Figure 9. Comparison of RCA slump.

3.5 Concrete Compressive Strength

Compressive strength testing was selected to represent the mechanical properties of concrete because concrete is excellent at resisting compressive loads. HGA RCA concrete has an average compressive strength value of 3% greater than the compressive strength of HG RCA concrete. HGA RCA concrete exhibits slightly higher strength because it is assumed to be due to additional treatment in production, namely the immersion in a chemical solution. The old mortar bond to the aggregate surfaces is a weak link so that the mortar material, which mostly consists of calcium oxide (CaO), silica dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3), can be transformed and released easier in an acidic environment (Tam et al., 2007b). Thus, the weak link in the HGA RCA decreases, and as a result, the strength increases. A comparison of the compressive strength values between the three types of concrete is presented in (Figure 10).

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In addition, compared to NCA concrete, either HGA RCA concrete or HG RCA concrete shows a lowering compressive strength The average compressive strength achieved by NCA concrete is 37.9 MPa; meanwhile, HGA RCA concrete and HG RCA concrete reach the average compressive strength of 36.7 MPa and 35.6 MPa respectively Furthermore, the difference in compressive strength values between NCA concrete and RCA concrete is in a range of 3.3%- 6.5%; thus it can be supposed that the quality of the two types of concrete is not significantly difference. Compared to other researchers using mechanical crushing method, RCA in producing concrete, a difference was found to be more than 26% between NCA and RCA concrete (Etxeberria et al., 2007); (Xiao et al., 2005). Therefore, these types of RCA can be considered as an ingredient for concrete because, with the same water-cement ratio mixture composition, RCA concrete reaches 95% compressive strength as NCA concrete on average. Moreover, the resulting compressive strength achieves more than 21 MPa, the minimum compressive strength required for structural concrete (SNI 2847-2019, 2019).

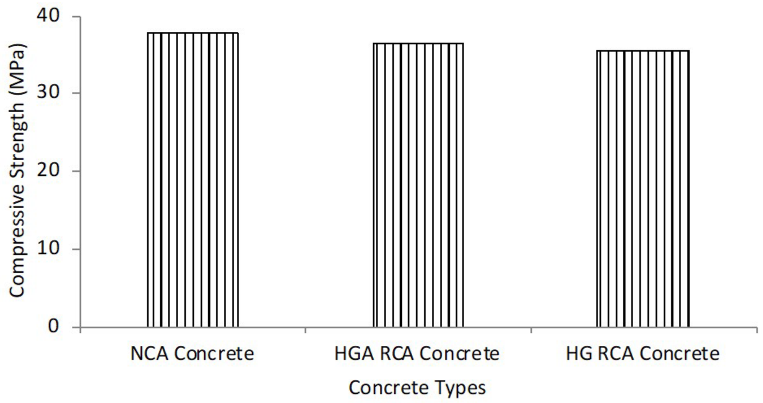

Figure 10. Concrete compressive strength.

3.6 Concrete Microstructures

To investigate more about the microstructure of concrete produced from recycled aggregates treated with the HGA and HG methods, especially to observe the interfacial transition zone (ITZ), scanning electron microscopy (SEM) was used. SEM was also conducted on NCA concrete to compare the ITZ set in RCA concrete.

At ×50 magnifications as illustrated by (Figure 11), it is observed that NCA concrete has a more regular boundary between the aggregate and cement paste surfaces. However, in RCA concrete, both HGA RCA and HG RCA types have more irregular boundaries between the RCA surfaces and mortar. The irregular boundaries are assumed because there is still a residual of the old mortar on the surface of the RCA.

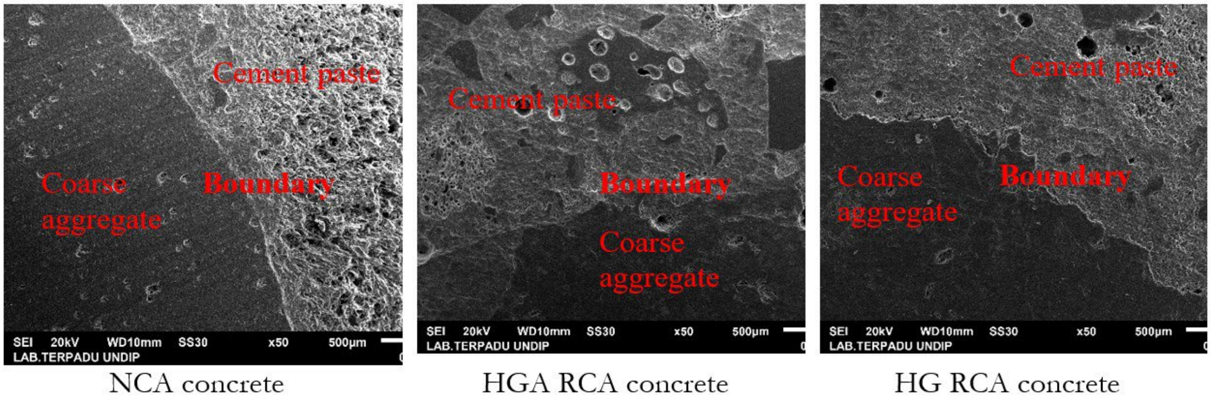

Figure 11. SEM images on ×50 magnifications.

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(Figure 12) shows SEM images with ×500 magnifications. Microcracks were noticed in the ITZ of concrete produced with NCA. These microcracks are visible surrounding the surface of the NCA. Similar to NCA concrete, microcracks are noticeable in the ITZ of RCA concrete. In addition, microcracks are also observed in the mortar for both types of RCA concrete. It is assumed that the microcracks found in this mortar are the ITZ between the remains of the old cement paste and the new cement paste. The ITZ between the old mortar and the new mortar on the HGA RCA concrete is more evident than that observed on the HG RCA concrete. Previous studies (Tam et al., 2007b); (Wang et al., 2020) have shown that when RCA is immersed in an acid solution of less than 0.8 mol concentration, it does not affect the properties of ITZ; however, in this study, it is recognized that the difference in HG and HGA treatments results in differences in the appearance of micro cracks.

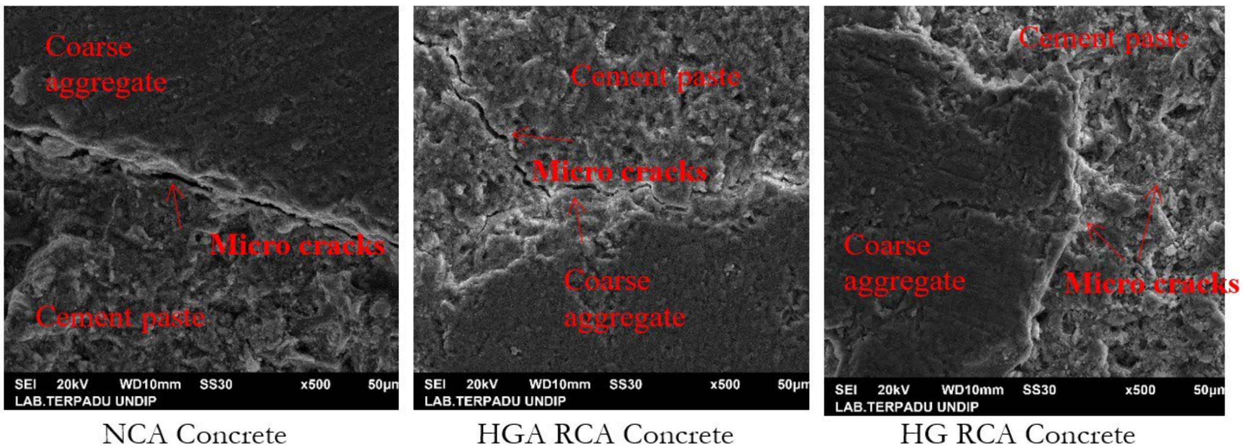

Figure 12. SEM images on ×500 magnifications.

The content of C-H and C-S-H are visible at a magnification of ×5000, as shown in (Figure 13). Either NCA or RCA concrete, shows that ITZ is dominated by the presence of $Ca(OH)_2$ compared to C-S-H. At this magnification, the size of the micro-cracks was also measured, and it was found the width of ITZ micro-cracks varies between 0.5 µm to 2 µm.

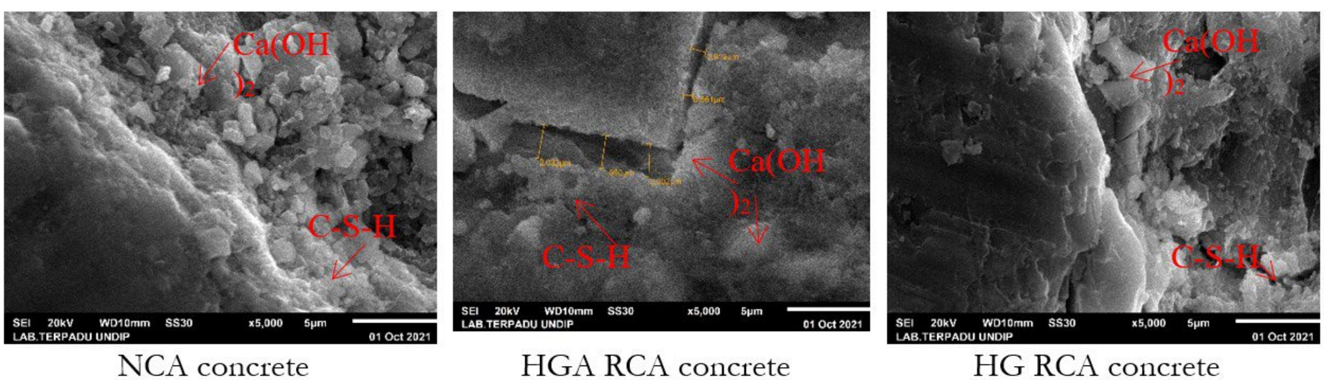

Figure 13. SEM images on ×5000 magnifications.

At ×8000 magnifications, some regions in the ITZ section are noticeable, as shown in (Figure 14). These areas are generally divided based on appearance, color, cracks, and shape. NCA concrete has three regions: coarse aggregate, micro-cracks, and new mortar. Furthermore, in RCA concrete, there are generally four areas: coarse aggregate, micro-cracks, old mortar, and new mortar. The new mortar has a darker color than the old mortar. In addition, the new mortar has finer and smaller fragments; therefore, it looks denser. The old mortar is less dense due to the heating process, which makes it weaker, and the grinding process attempts to disintegrate and remove it from the surface of the recycled aggregate.

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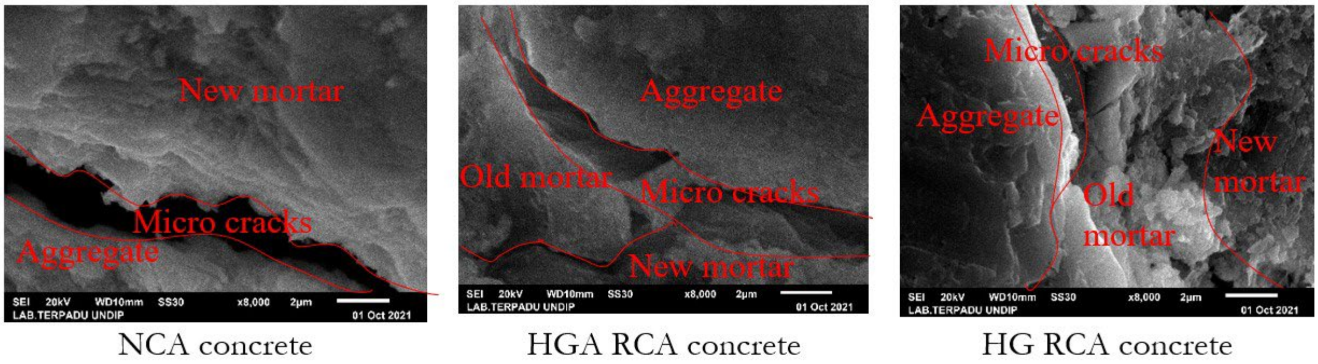

Figure 14. SEM Images on ×8000 magnifications

3.7 Economic Aspect

Even though the waste concrete used in this study was obtained free of charge, the production of HG RCA and HGA RCA still requires costs because several processes are involved during the production, for instance, labor, electricity, equipment, transportation, and other materials. On the other hand, natural aggregate can be purchased commercially. The costs calculated in this study are based on standardized local prices for materials and services in the 2023 financing year. In this case, the production price from RCA in the laboratory includes equipment rental, such as ovens and grinding machines, labor pay, and acid solution purchasing. Electricity for equipment operations and water for cleaning materials are included in the rental equipment. The production price of RCA is compared to the purchasing price of the natural aggregate of crushed stone with the same grain size and volume.

The production prices for HG and HGA RCA are 683 thousand IDR per m^3 and 823 thousand IDR per m^3, respectively. HGA RCA has a higher production price due to additional chemical treatment. Meanwhile, the price for procuring NCA with the same volume is 532 thousand IDR. Thus, the production cost of the two types of RCA is more expensive than the cost of purchasing the NCA. HGA RCA costs 1.55 times the cost of NCA, and HG RCA costs 1.28 times the price of NCA. A comparison of normalized prices is shown in (Figure 15).

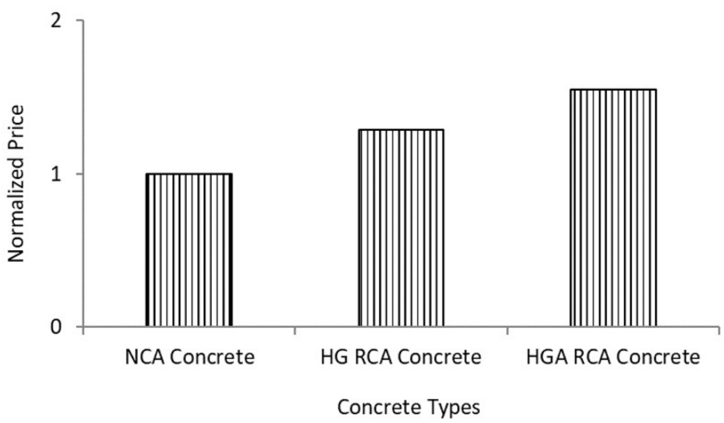

Figure 15. Production cost.

The production cost of concrete made from RCA is also highlighted by (Tošić et al., 2015). Concrete with RCA costs 30% more than concrete made with NCA. Furthermore, it is recommended not to replace RCA with NCA entirely on the mixture but as a partial replacement for NCA in concrete. Thus, the costs are relatively inexpensive but still maintain the concept of sustainable concrete.

From an economic overview, the higher RCA production cost is still a challenge. However, when regarded as a massive benefit to the environment both in terms of reducing the landfilling of construction demolition waste and reducing the exploitation of natural aggregates. In addition, based on the results of this study, the quality of the RCA product and RCA concrete is almost the same as that of natural aggregates and NCA concrete,

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respectively. Research with a focus on reducing production costs is also suggested by (Makul et al., 2021) to achieve cost-effective RCA to support sustainable and green concrete.

4. Conclusion

This article discusses RCA extracted from concrete waste, which is treated physically, mechanically, and chemically to improve the quality used as a material for producing new concrete. The review is not only in terms of aggregate quality but also the production costs. In addition, the compressive strength and microstructure of concrete made from RCA are also discussed. RCA quality is similar to NCA and meets the requirements as a concrete constituent material in terms of gradation, fineness modulus, specific gravity, and water absorption. The quality results from the treatment in which RCA undergoes several processes; therefore, the mortar content on the surfaces remains only 4% for HGA RCA concrete and 6% for HG RCA concrete.

Moreover, RCA concrete reaches 95% compressive strength as NCA concrete on average. The resulting compressive strength achieves more than 21 MPa, the minimum compressive strength required for structural concrete. Furthermore, the residual mortar on the RCA surface makes a difference in the microstructural properties between RCA concrete and NCA concrete. ITZ on RCA concrete shows more visible microcracks, irregular boundaries between aggregate surface and cement paste, and more than one ITZ appearance. Even though the mortar content has already significantly reduced after the thermal, mechanical, and chemical processes, the remaining old mortar still affects the microstructural properties of RCA concrete.

The next challenge is the production cost which is still more expensive than purchasing natural aggregates. It is assumed that this economic aspect is still being analyzed on a limited production basis for laboratory purposes. Further research is expected to be able to provide much cleaner RCA concrete free from old mortar or reduce production costs by continuing to use a simpler technology that can be applied in developing countries. Therefore, sustainable concrete using recycled aggregate can be established as one of the construction materials globally.

5. Notes on Contributors

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