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Effect of repeated use of recycled aggregate on some properties of concrete

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Keywords: concrete mix design, recycled aggregate concrete, recycled powder concrete, repeated recycling, closed-loop recycling.

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Abstract

Over the past few decades, recycled aggregate obtained from concrete waste has been used as a raw material in concrete structures. The term 'recycled aggregate', commonly used until recently, typically refers to aggregate that has undergone one round of recycling. This one-time recycling, however, fails to adequately address sustainable development, and the feasibility of multiple-time recycling still remains questionable.

The present dissertation investigates the effect of repeated recycling of concrete waste on various properties of new-made concrete, and comprises two review articles and three original research articles published in internationally reputable journals:

- In the first review article, the relation between the quality of recycled concrete aggregate and the performance of concrete was analyzed.
- In the second review article, the effectiveness of a mix design, entitled an equivalent mortar volume method, was analyzed in terms of the performance of recycled aggregate concrete.
- In the third article, of a research type, the effect of repeated recycling of concrete waste as recycled coarse aggregate on the mechanical and durability of new-made concrete was studied.
- In the fourth research article, to deepen the analysis on recycling, recycled materials with different particle sizes obtained from concrete waste replaced coarse aggregate, fine aggregate, and cement in concrete, respectively, and the effect of these replacements on concrete properties was assessed.
- In the fifth article, of a research type, the effect of powders obtained from repeated recycling of concrete waste on the properties of concrete as a partial cement replacement was investigated.

Each of the presented studies provides new initiatives for repeated recycling and complete recycling of concrete waste, and can contribute to the establishment of a knowledge system for multiple recycling of concrete waste in the context of environmental protection.

Keywords: concrete mix design, recycled aggregate concrete, recycled powder concrete, repeated recycling, closed-loop recycling.

Streszczenie

W ciągu ostatnich kilku dekad kruszywo z recyklingu uzyskane z odpadów betonowych jest wykorzystywane jako surowiec w budownictwie, także w celach konstrukcyjnych. Termin "kruszywo z recyklingu" zazwyczaj odnosi się do kruszywa, które zostało poddane jednemu cyklowi kruszenia. Ten jednorazowy recykling nie uwzględnia jednak w odpowiedni sposób zrównoważonego rozwoju, a z drugiej strony - realizacja wielokrotnego kruszenia nadal pozostaje wątpliwa.

Niniejsza rozprawa doktorska bada wpływ wielokrotnego recyklingu odpadów betonowych na różne właściwości nowego betonu i obejmuje dwa autorskie artykuły przeglądowe oraz trzy oryginalne artykuły badawcze. opublikowane w renomowanych czasopismach międzynarodowych:

- W pierwszym artykule przeglądowym przeanalizowano związek między jakością kruszywa betonowego pochodzącego z recyklingu a właściwościami użytkowymi betonu.
- W drugim artykule przeglądowym dokonano analizy skuteczności projektowania mieszanki za pomocą metody równoważnej objętości zaprawy pod kątem jakości betonu z kruszywem pochodzącym z recyklingu.
- W trzecim artykule, o charakterze badawczym określono wpływ wielokrotnego recyklingu odpadów betonowych jako gruboziarnistego kruszywa z recyklingu na właściwości mechaniczne i trwałość nowego betonu.
- W czwartym artykule badawczym, w celu pełniejszego przeanalizowania recyklingu, materiały pochodzące z recyklingu o różnych rozmiarach cząstek uzyskanych z odpadów betonowych zastąpiły odpowiednio kruszywo grube, kruszywo drobne i cement w betonie i oceniono wpływ tych zamienników na właściwości betonu.
- W piątym artykule, o charakterze badawczym. przedstawiono i przeanalizowano wyniki badań nad wpływem materiałów proszkowych uzyskanych z wielokrotnego recyklingu odpadów betonowych na niektóre właściwości betonu jako częściowego zamiennika cementu.

Każde z przedstawionych badań inspiruje do podjęcia nowych przedsięwzięć naukowych w zakresie wielokrotnego recyklingu i pełnego recyklingu odpadów betonowych i może przyczynić się do stworzenia systemu wiedzy na temat rozszerzonego recyklingu odpadów betonowych w aspekcie ochrony środowiska.

Słowa kluczowe: projektowanie mieszanki betonowej, beton z kruszywem z recyklingu, beton proszkowy z recyklingu, recykling powtórny, recykling w pętli zamknię.

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1. Introduction

1.1 Aim

The aim of this doctoral dissertation is to evaluate the effect of repeated recycling of concrete waste on the properties of the new-made concrete. Specifically, the research is divided into the following two parts:

1. Evaluation of concrete incorporating repeatedly-recycled coarse aggregate and mitigation of performance degradation caused by repeated recycling.

2. Investigation of the effect of using fine particles generated from repeated recycling of concrete waste as a partial replacement for cement on the properties of concrete.

For the research aims, the following details are conducted:

- The influence of replacing natural aggregate by recycled concrete aggregate on the properties of concrete is summarized. The grade of recycled concrete aggregate is evaluated based on its physical characteristics, such as water absorption and density, and the factors that affect the quality of recycled concrete aggregate are reviewed. Additionally, the relation between the quality of recycled concrete aggregate and the properties of the corresponding concrete is analyzed.
- The effect of repeated recycling of concrete waste on the properties of new-made concrete is investigated. Concrete waste is crushed to be recycled coarse aggregate, which is subsequently used as a raw material for concrete. By repeating this procedure, various properties of concrete with three different recycling cycles are evaluated as per standardized test methods.
- In order to mitigate the performance degradation of concrete resulting from repeated recycling, adjustments are made to the concrete mix proportions, considering the variations in characteristics of recycled concrete aggregate with an increasing number of recycling cycles. The properties of these modified concretes are then evaluated and compared with those of conventionally-designed concrete.
- To achieve zero-waste, the utilization of fine particles generated from repeated recycling of concrete, specifically from crushing concrete waste to produce recycled coarse aggregate, is discussed. The fine powder is employed as partial replacement for cement, and its influence on the principal properties of concrete is investigated.

1.2 Motivation

As a result of the persistent endeavors by stakeholders in the realm of concrete waste utilization, the application of recycled aggregate concrete has been successfully actualized in modern concrete structures, encompassing buildings, bridges, and roads [1,2]. The term "recycled concrete aggregate", commonly used thus far, refers to aggregate obtained by crushing concrete made from natural aggregate. More precisely, it denotes aggregate that have undergone one cycle of recycling. From the perspective of resource circulation, it is essential to assess the feasibility of repeated recycling of recycled aggregate concrete, as concrete made of the once-recycled aggregate should undergo subsequent recycling. In particular, emphasis should be placed on minimizing the detrimental effects of the repeated recycling on the performance of concrete reported in previous studies [3–7]. Another factor to be considered in the repeated recycling of concrete is the utilization of the fine particles generated, which has not been studied yet. The utilization of recycled powder generated in the concrete recycling process is crucial for achieving the complete recycling of concrete waste. While some studies [8,9] incorporate recycled aggregate and recycled powder for complete recycling, the sustainability of this recycling approach raises concerns, given that the effect of repeated recycling remains unassessed. Through the investigation of repeated and complete recycling of concrete waste in this study, the achievement of zero waste in concrete can be realized (Figure 1).

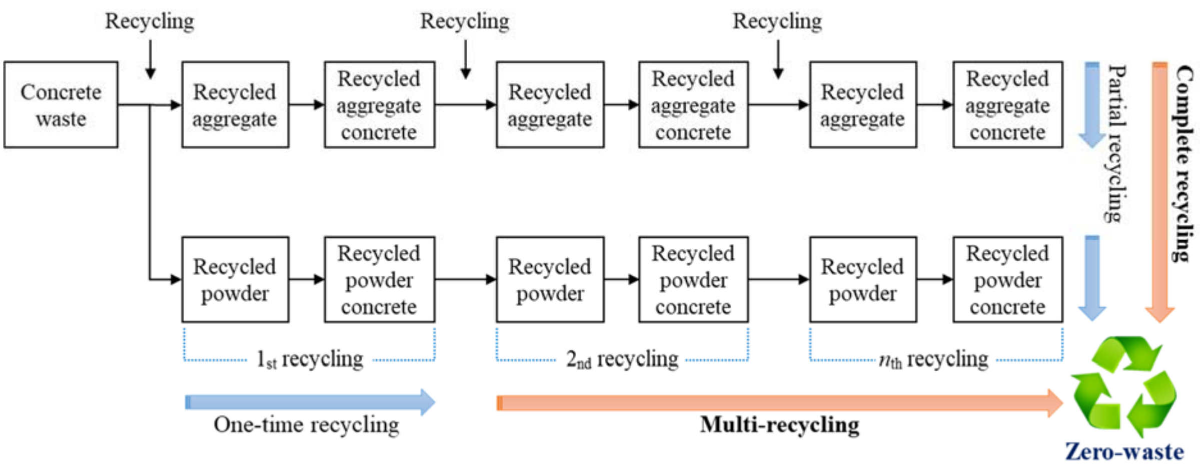

Figure 1. Concept of repeated and complete recycling of concrete waste.

1.3 Scope of the dissertation

This doctoral dissertation is a collective work and consists of the following five review and original research publications [A1]-[A5]. Each publication focuses on a distinct topic related to the complete and repeated recycling of concrete waste (Figure 2).

[A1] **Kim, J.** (2022). Influence of quality of recycled aggregates on the mechanical properties of recycled aggregate concretes: An overview. Construction and Building Materials, 328, 127071. DOI: 10.1016/j.conbuildmat.2022.127071
IF: 7.693, MEiN point: 140, Non-self-citation: 41, Author's contribution: 100%

[A2] **Kim, J.** (2021). Properties of recycled aggregate concrete designed with equivalent mortar volume mix design. Construction and Building Materials, 301, 124091. DOI: 10.1016/j.conbuildmat.2021.124091
IF: 7.693, MEiN point: 140, Non-self-citation: 16, Author's contribution: 100%

[A3] **Kim, J.**, Grabiec, A. M., Ubysz, A., Yang, S., & Kim, N. (2023). Influence of mix design on physical, mechanical and durability properties of multi-recycled aggregate concrete. Materials, 16(7), 2744. DOI: 10.3390/ma16072744
IF: 3.748, MEiN point: 140, Non-self-citation: -, Author's contribution: 45%

[A4] **Kim, J.**, Grabiec, A. M., & Ubysz, A. (2022). An experimental study on structural concrete containing recycled aggregates and powder from construction and demolition waste. Materials, 15(7), 2458. DOI: 10.3390/ma15072458
IF: 3.748, MEiN point: 140, Non-self-citation: 9, Author's contribution: 70%

[A5] **Kim, J.**, & Jang, H. (2022). Closed-loop recycling of C&D waste: Mechanical properties of concrete with the repeatedly recycled C&D powder as partial cement replacement. Journal of Cleaner Production, 343, 130977. DOI: 10.1016/j.jclepro.2022.130977
IF: 11.072, MEiN point: 140, Non-self-citation: 19, Author's contribution: 70%

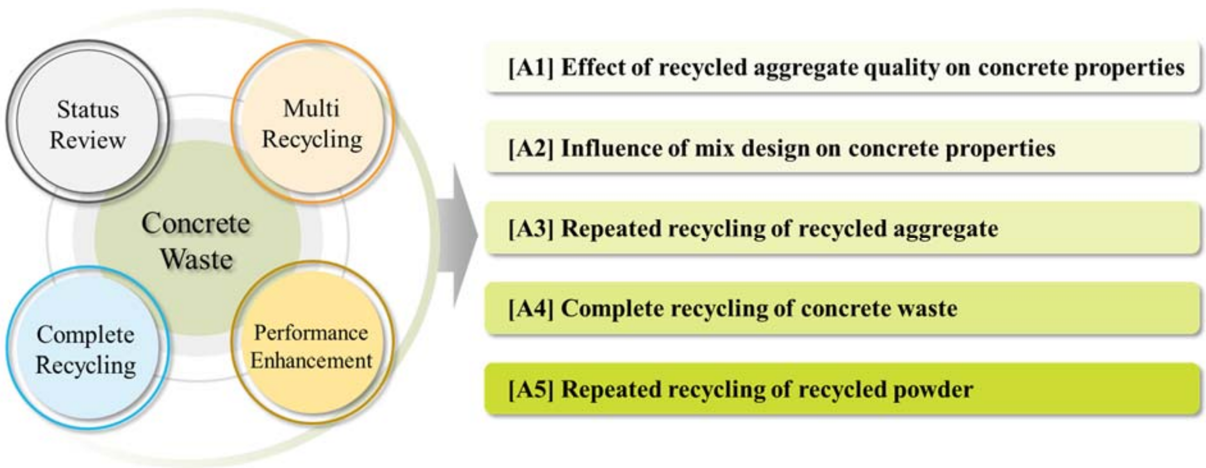

Figure 2. Research scope of the dissertation.

The article [A1] presents a comprehensive review on the influence of recycled aggregate quality on concrete properties. In the article, the factors affecting the quality of recycled aggregate are discussed and the relation between quality of recycled aggregate and concrete properties is presented.

The article [A2] presents a literature review on the equivalent mortar volume (EMV) mix design, which is adopted to compensate for the performance degradation in concrete resulting from the replacement of natural aggregate with recycled aggregate. The article briefs the concept of the EMV mix design and presents its effectiveness in enhancing the properties of recycled aggregate concrete, in comparison to the conventional mix design method.

In article [A3], the EMV mix design reviewed in [A2] is applied to concrete with repeatedly-recycled coarse aggregate, and its influence on various properties of EMV-based concretes is investigated over the number of recycling cycles.

The articles [A4] and [A5] focus on the utilization of fine particles produced during the crushing of concrete waste in order to achieve zero-waste. In [A4], the concrete waste is processed into recycled materials with different particle sizes. These recycled materials are then employed as replacements for coarse aggregate, fine aggregate, and cement in concrete. In [A5], the repeatedly-recycled concretes that incorporates the recycled coarse and fine aggregates obtained in [A4] are prepared through a series of concrete crushing and manufacturing. The recycled powders generated from the concrete crushing are used as partial cement replacement and their effect on concrete properties is explored.

Table 1 classifies the five publications presented in this dissertation by the number of recycling of concrete waste and recycled materials addressed. According to the author's review articles [A1] and [A2] on the recycling of concrete waste, majority of previous studies have dealt with partial recycling, particularly, on the use of recycled coarse aggregate obtained from natural aggregate concrete (i.e., one-off recycling). To expand on these limitations, the author's original research articles explore repeated- and complete recycling of concrete waste. This emphasizes the novelty of this dissertation, distinguishing it from previous research.

Table 1. Classification of concrete recycling based on the number of times recycled and recycled material.

No.	Research type	Category	Main recycled material
[A1]	Review	One-time and partial recycling	Recycled coarse aggregate
[A2]	Review	One-time and partial recycling	Recycled coarse aggregate
[A3]	Research	Repeated recycling	Repeatedly-recycled coarse aggregate
[A4]	Research	One-time and complete recycling	Recycled coarse- and fine aggregate Recycled powder
[A5]	Research	Repeated and complete recycling	Repeatedly-recycled powder

2. A literature review on the influence of recycled aggregate quality on the properties of concrete

2.1 Summary of article [A1]

In Chapter 2, a literature review is conducted on the effect of the use of recycled aggregate on the properties of concrete, and the full text of the article [A1] is attached on page 31.

It is widely recognized that the replacement of natural aggregate by recycled aggregate generally leads to a reduction in the performance of recycled aggregate concrete. This performance loss is attributed to the two-phase characteristics of recycled aggregate, consisting of old mortar and original aggregate, unlike natural aggregate, which is a single-phase material. The presence of old mortar in recycled aggregate lowers its density and increases its water absorption, which is considered the primary cause of the deterioration in aggregate quality [10,11].

According to some regulations, recycled aggregate can be classified into high, medium, and low quality based on its physical characteristics such as density and water absorption [12–14], however, a comprehensive review on the influence of recycled aggregate quality on concrete performance has not been studied. Through establishing the relationship between the quality of recycled aggregate and the properties of concrete, a deeper understanding of the influence of recycled aggregate can be gained, thereby facilitating the efficient utilization of recycled aggregate. Therefore, the article [A1] reviews previous studies on recycled aggregate concrete. Based on the reported water absorption and density of recycled aggregate, quality is classified into three grades (high-, medium-, and low-quality), and the following investigations are conducted:

- Key factors influencing the physical characteristics of recycled aggregate.
- The influence of physical characteristics of recycled aggregate on the properties of concrete.

A literature review indicates that the content of old mortar is a significant factor that influences the physical characteristics of recycled aggregate. This old mortar content is governed by various parameters, including the number of recycling cycles of concrete waste, the strength of parent concrete, and the treatment method applied for recycling:

- The old mortar content of recycled aggregate increases with the number of recycling cycles of concrete. That is, the quality of recycled aggregate obtained from repeatedly-recycled concrete is generally lower (i.e., lower density and higher water absorption) than that obtained from one-time recycled concrete [3,5,15,16].

- The quality of recycled aggregate is also dependent on the quality of its parent concrete. The dense pore structure of high-strength concrete enhances the quality of the recycled aggregate obtained from it, while conversely, the quality is diminished in the case of low-strength concrete [17–20].
- The content of old mortar is affected by the treatment method of concrete waste. The quality of recycled aggregate can be improved by removing old mortar through multiple crushing, heating, and chemical solution treatment [14,15].

The quality of recycled aggregate has a direct impact on the performance of concrete, proportionate to the replacement ratio. When utilizing high-quality recycled aggregate, the performance of concrete is comparable to, and often surpasses, that of natural aggregate concrete. Conversely, as medium and low-quality recycled aggregates are employed, the performance of the concrete progressively declines.

Given that the utilization of high-quality recycled aggregate can further enhance concrete performance, various methods for removing old mortar from recycled aggregate have been discussed and proposed: microwave method [21,22], acid treatment [23], chemico-thermal treatment [24], biotreatment [25]. However, apart from their efficiency, certain methods demand specialized equipment and additional fuel and energy, which poses challenges in their practical application. For example, multiple-time crushing decreases the recovery rate of recycled aggregate from concrete waste [26], and thermo-mechanical treatment consumes approximately 36-62 times more energy than traditional mechanical crushing [27]. Therefore, it is desirable to enhance the properties of concrete, preferably in a way that does not entail substantial resource consumption. Notably, the utilization of low-quality recycled aggregate can offer advantages in terms of time, cost, and energy savings. The detrimental effects on concrete performance resulting from the incorporation of low-quality recycled aggregate can be partially mitigated by applying a certain concrete mix design method that takes into account its characteristics. This approach is thoroughly reviewed in the article [A2].

2.2 Author’s achievement in article [A1]

The key research findings and achievements presented in article [A1] include:

- Factors affecting the quality of recycled aggregate are identified.

- The effect of recycled aggregate quality on the fresh and hardened properties of concrete is overviewed.
- Despite the favorable influence of high-quality recycled aggregate on the performance of concrete, the resources and energy required for its production are high. This study suggests the necessity of utilizing medium and low-quality recycled aggregate.

3. A literature review on the effect of mix design considering the characteristics of recycled aggregate on the properties of concrete

3.1 Summary of article [A2]

As reviewed in the article [A1], old mortar in recycled aggregate adversely affects the properties of recycled aggregate concrete. In the study [28], it is pointed out that the old mortar increases the mortar volume of recycled aggregate concrete compared to that of natural aggregate concrete, while reducing the original aggregate volume accordingly. In addition, the authors considered the increased total mortar of recycled aggregate concrete (i.e., the sum of old mortar in recycled aggregate and fresh mortar) as the cause of the inferiority, proposing an equivalent mortar volume (EMV) method to adjust material proportions of recycled aggregate concrete. The concept of EMV mix design regards recycled aggregate as a two-phase material, consisting of original aggregate and old mortar. In this approach, the old mortar is treated as mortar rather than aggregate. Consequently, the fresh mortar volume is reduced by the same amount as the old mortar volume in the recycled aggregate. As a result, the mortar volume in both natural aggregate concrete and EMV-based recycled aggregate concrete is equivalent. It has been reported that the mix proportion of recycled aggregate concrete adjusted by the EMV method not only strengthens the hardened properties of recycled aggregate concrete [29–33], but also has environmental and economic benefits such as saving water, sand, and cement required for fresh mortar [34]. Chapter 3 reviews the literature on the effect of the EMV mix design on concrete properties, and the full text can be found on page 43. This study focuses on the following key points:

- The effectiveness of the EMV mix design method in the properties of recycled aggregate concrete.
- The quality of recycled aggregate used in EMV-based concrete.

Based on the literature review, compared with the conventional mix design, the application of the EMV method has shown improvements in mechanical strength [29,35,36], elastic modulus [28,36,37], chloride and freeze-thaw resistance [33,37–39] and drying shrinkage of recycled aggregate concrete [35,36,39–41].

Several studies have reported that the utilization of medium-quality recycled aggregate (with density of 2.3~2.5 g/cm^3 and water absorption of 3~5%) and low-quality recycled aggregate (density less than 2.3 g/cm^3 and water absorption 5~7%) in EMV-based concrete can result in higher compressive strength and elastic modulus compared to conventional-based concrete [28,35–37,42]. In addition, in these studies, the reduction of materials such as water, sand, and cement used in concrete production is saved by up to 29%. Nevertheless, it should be noted that the application of the EMV method does not always guarantee an improvement in concrete properties. For instance, in the article [35], when using 50% recycled aggregate replacement, EMV-based concrete exhibits an 8% increase in compressive strength compared to conventional-based concrete. However, at 100% replacement, the compressive strength of EMV-based concrete is 8% lower. This discrepancy arises because the mix proportion is not the sole determining factor influencing concrete performance. Further discussion on this matter can be found in the article [A3].

3.2 Author's achievement in article [A2]

The main findings and achievements in the article [A2] are as follows:

- The effectiveness of the EMV mix design is demonstrated in terms of concrete properties and resource savings, compared to the conventional mix design.
- Medium and low-quality recycled aggregates can be effectively utilized in EMV-based concrete, eliminating the need for additional equipment and reducing the energy demand associated with producing high-quality recycled aggregate.

4. An experimental study on repeated recycling of concrete waste as recycled coarse aggregate in concrete

4.1 Summary of article [A3]

One-time recycled aggregate, which is obtained by crushing natural aggregate concrete, is in use for actual concrete structures [1,2,43]. Accordingly, research on the recycling of concrete waste extends beyond single-time recycling to multiple-time recycling. Previous studies [7,44] commonly point out that repeated recycling of concrete leads to a gradual increase in the old mortar content in recycled aggregate, resulting in a reduction of properties of concrete subjected to multiple recycling cycles. This means that the mortar volume in repeatedly-recycled concrete increases gradually with each recycling cycle, while the original aggregate volume decreases accordingly. This change in material proportion by the presence of old mortar is one of the underlying causes of concrete degradation, as identified in a study [28]. It also explains why concrete subjected to a higher number of recycling cycles exhibits lower performance compared to concrete with fewer recycling cycles. In Chapter 4, an experimental study is conducted to address the performance degradation of concrete resulting from repeated recycling. The full text of the study is attached on page 55.

In this study, concretes with three different recycling cycles (i.e., once-, twice- and three-times recycled concretes) is prepared by repeating the process of making and crushing concrete, and their properties are investigated. As a mix design, the EMV method, which keeps the total mortar volume of concrete constant regardless of the old mortar content, is employed for repeatedly-recycled concrete. The replacement rates of natural aggregate with recycled aggregate are set at 50% and 100%, respectively. This approach is based on the hypothesis that an EMV mix design, which contributes to the enhanced performance of once-recycled concrete as reviewed in the author's literature study [A2], may also help alleviate the performance degradation of repeatedly-recycled concrete.

In this study, the following aspects are investigated:

- Characteristics of recycled aggregates (density, water absorption and old mortar content) obtained from repeatedly-recycled concrete.
- The effect of the EMV mix design on properties of repeatedly-recycled concrete compared to the conventional mix design (slump, density, water absorption, mechanical strength, drying shrinkage and chloride resistance).

- The combined effect of the EMV mix design and the recycled aggregate replacement rate on properties of repeatedly-recycled concrete.

Based on the experimental data, the old mortar content in recycled aggregate increases gradually with an increasing number of recycling cycles, indicating a degradation in its quality, characterized by low density and high water absorption. These quality changes have a negative impact on the properties of recycled concrete designed by the conventional mix design. As a function of the number of recycling cycles, the slump, density, mechanical strength, and chloride resistance decrease, while water absorption and drying shrinkage increase.
In the fresh state, concrete designed with the EMV method records greater slump loss than that of conventional-based concrete due to the lack of fresh mortar. At a replacement rate of 50%, the hardened properties of the EMV-based concrete show no remarkable change over the three recycling cycles. Compared to the once-recycled concrete, the variation in density of the twice- and three-times recycled concretes is within ± 1%, and the 28-day compressive strength is within ± 3%.

However, even if the same mix design is adopted, the properties of EMV-based concrete change depending on the recycled aggregate replacement rate. The EMV-based concrete at 100% replacement shows a lower density and higher water absorption than those of the EMV-based concrete at 50% replacement, indicating that there are more voids inside the concrete with 100% replacement. Pores in concrete weaken its resistance to external forces, leading to a decrease in mechanical strength, and facilitate the movement of harmful substances such as chloride ions. Additionally, as water evaporates from the pores, the concrete becomes susceptible to shrinkage deformation [45]. As a result, the EMV-based concrete at a 100% replacement rate exhibits the lowest mechanical strength and chloride resistance among all the prepared concretes.

This discrepancy is because, as mentioned in the article [A2], the properties of concrete are not solely influenced by material proportions. The strength of concrete is significantly governed by the interfacial transition zone (ITZ) of aggregate and cement paste, particularly the ITZ between old mortar and fresh cement paste is considered the weakest link [46]. Hence, the presence of 50% natural aggregates in the EMV-based concrete with 50% recycled aggregate contributes to mitigating performance loss by reducing the ITZ between the old mortar and new cement paste. However, reducing the replacement rate of repeatedly-recycled aggregates alone cannot prevent the performance loss of concrete. Previous studies have shown that when using 25% repeatedly-recycled aggregate in conventional-based concrete, there is a clear reduction in the strength and chloride resistance [6,15,47]. Therefore, to achieve repeated recycling of concrete without compromising its properties, it may be necessary to employ a combination of methods, such as the EMV mix design and optimized replacement rate. This study demonstrates the combined effect of such approaches.

4.2 Author’s achievement in article [A3]

The article [A3] highlights the following key research achievements:

- The quality of recycled aggregate and the performance of conventional-based concrete gradually decrease as the number of recycling cycles increases. This finding is in line with the results reported in previous studies and contributes to the establishment of knowledge system for repeated recycling of concrete.
- The repeated recycling of concrete without loss of properties is achieved through the combination of EMV mix design and adjustment of the aggregate replacement rate.
- In particular, low-quality recycled aggregate is utilized for the twice- and three-times recycled concretes. This highlights the eco-friendly approach of this study, as it eliminates the need for additional resources and energy required to produce high-quality recycled aggregate.

5. An experimental study on the utilization of recycled materials obtained from concrete waste in new-made concrete.

5.1 Summary of article [A4]

Achieving zero-waste requires systematic research on the utilization of all size fractions of recycled materials generated from concrete waste. Some studies point out that research on concrete recycling has primarily focused on the production and utilization of recycled coarse aggregate, with relatively less attention given to recycled fine aggregate and recycled powder, which can replace sand and cement [48,49]. Chapter 5 discusses the complete recycling of concrete waste to achieve zero waste. Concrete waste is crushed to obtain recycled coarse aggregate, recycled fine aggregate, and recycled powder. The obtained materials replace natural coarse aggregate, sand and cement in concrete, respectively, and their effect on the properties of concrete is evaluated. The full text of this work is provided on page 71. This study investigates:

- The effect of recycled coarse aggregate (4.75–25 mm), recycled fine aggregate (0.15–4.75 mm), and recycled powder (smaller than 0.15 mm) on concrete properties (air content, slump, compressive strength, splitting tensile strength and elastic modulus).
- The effect of replacement rates (30%, 60%, 100% for recycled coarse- and fine aggregates; 10%, 20%, 30% for recycled powder) on concrete properties.
- Environmental and cost benefits of concrete containing recycled aggregates and powder.

The experimental results show that the workability and strength of concrete decrease as the replacement rate increases, regardless of the type of recycled material used. For concrete incorporating recycled coarse and fine aggregates, the performance decline occurs in the following order: concrete with recycled fine aggregate (-12%), recycled coarse aggregate (-15%), and simultaneous use of recycled coarse and fine aggregates (-19%).

The strength of concrete containing recycled powder decreases in a nonlinear manner as the replacement rate increases. Among all the prepared recycled concretes, except for natural aggregate concrete, concrete with 10% recycled powder exhibits the highest strength. However, at a 30% replacement rate, the strength of recycled powder concrete is 17~19% lower than that of concrete with 100% recycled coarse and fine aggregates. Despite this strength loss, all concretes can be applied for structural purposes under various environmental exposure conditions based on PN-EN 206:2016 [50].

In cost and environmental analyses, concrete with the recycled materials has a lower production cost and global warming potential compared to those of natural aggregate concrete. In particular, due to the high unit cost and carbon dioxide emissions associated with cement production, recycled powder concrete offers greater cost value (i.e., production cost divided by compressive strength) and eco-efficiency (i.e., global warming potential divided by compressive strength) in comparison to natural aggregate concrete.

5.2 Author's achievement in article [A4]

The main research findings derived from the article [A4] are as follows:

- The effect of utilizing recycled materials obtained from concrete waste as replacements for coarse aggregate, sand, and cement on concrete properties is established.
- The applicability of concrete with recycled coarse and fine aggregates, and recycled powder as structural concrete is presented based on a European standard. All prepared concrete can be used for structural purposes under different environmental exposure conditions.
- Environmental and cost-benefit analyses of recycled concrete, considering its performance, offer valuable insights for the effective recycling of concrete waste. For instance, utilizing concrete waste in powdered form, rather than as aggregate, can be more efficient. However, the optimal approach may vary depending on external factors such as the quantity of waste generated, treatment methods, and equipment.

6. An experimental study on the effect of recycled concrete powders obtained from repeated recycling of concrete waste on the properties of concrete.

6.1 Summary of article [A5]

As mentioned in the previous chapter, various researchers, including the author, conduct investigations on the repeated recycling of concrete. However, to the author's knowledge, no study has been conducted using recycled powder generated from the repeated recycling of concrete as a replacement for cement. Cement production ranks as the third-largest contributor to anthropogenic carbon dioxide emissions [51] and is associated with environmental concerns, including emissions of carbon monoxide and various heavy metals [52]. Thus, reducing reliance on cement is emphasized as a significant sustainability challenge facing the construction industry [53]. Chapter 6 investigates the effect of repeatedly-recycled concrete powders on the properties of concrete when used as a partial replacement for cement. It also explores the potential for implementing a closed-loop recycling system for concrete waste. The full text of this study can be found on page 89 of this doctoral dissertation.

For the experiment, recycled concrete powders with three different recycling cycles are obtained through a series of concrete production and crushing processes. These recycled powders are used to replace cement at mass percentages of 10%, 20%, and 30%. In this work, the following points are mainly investigated:

- The effect of the replacement rate of repeatedly-recycled concrete powder on the properties of concrete (slump, air content, mechanical strength and elastic modulus).
- The effect of the number of recycling cycles of repeatedly-recycled concrete powder on the properties of concrete.
- Environmental and cost-benefit of concrete with repeatedly-recycled concrete powder.

The experimental results have demonstrated that both the replacement rate and the number of recycling cycles of recycled concrete powder are parameters that negatively affect the properties of concrete. Specifically, among the two parameters, the replacement rate seems to have a greater influence on the concrete properties compared to the number of recycling cycles. For instance, concrete containing 10% of three-times recycled concrete powder exhibits better performance than concrete containing 20% of once-recycled concrete powder.

While all concretes incorporating recycled concrete powder show lower performance than natural aggregate concrete, it should be understood that the objective of using recycled powder in concrete is not to surpass the performance of natural aggregate concrete. Instead, the aim is to achieve an economically viable and environmentally friendly concrete that meets the intended requirements. For instance, when 10% recycled concrete powder is used in concrete, it exhibits significant competitiveness by achieving approximately 95% of the performance of natural aggregate concrete in terms of compressive strength and elastic modulus, even after undergoing three cycles of recycling. With this in mind, the target strength can be achieved even with the addition of 20% of three-times recycled concrete powder. Furthermore, the use of recycled powder as cement replacement has several environmental benefits, including carbon emission reduction, resource conservation, and landfill space preservation. In the analysis of economic and environmental benefits, the use of recycled concrete powder up to 20% during the three-times of recycling not only achieves the desired strength but also provides better cost value and eco-efficiency compared to natural aggregate concrete.

6.2 Author's achievement in article [A5]

The research achievements outlined in article [A5] are as follows:

- This work has originality in that it utilizes repeatedly-recycled concrete powder, which is inevitably generated during concrete recycling, as a partial replacement for cement.
- The effect of repeatedly-recycled concrete powder on the properties of concrete is provided based on the number of recycling cycles and replacement rate.
- Within a certain range of replacement rates (up to 20% in this study), the utilization of recycled concrete powder exhibits superior cost value and eco-efficiency compared to natural aggregate concrete.
- This work accomplishes the realization of a closed-loop recycling system, enabling the zero-waste and repeated recycling of concrete waste without the need for landfill.

7. Final remarks and conclusions

This dissertation, comprised of five publications, of the author as individual or co-author but in all cases as a lead author, thoroughly investigates the effect of repeatedly-recycled aggregate and recycled powder derived from concrete waste on the properties of new-made concrete.

In the article [A1], a literature study, made by the author, on the relationship between the quality of recycled aggregate and the properties of recycled aggregate concrete is conducted. Generally, concrete containing recycled aggregate exhibits inferior properties compared to natural aggregate concrete. However, the study reveals that high-quality recycled aggregate contributes to the enhanced performance of recycled aggregate concrete. On the other hand, the production of high-quality recycled aggregate requires higher energy consumption. Moreover, when concrete waste is recycled multiple times, the quality of the recycled aggregate obtained from it progressively degrades due to the increased old mortar content. Based on these findings, the study suggests the necessity of utilizing medium and low-quality recycled aggregates.

Therefore, in the article [A2], a literature study on the properties of recycled aggregate concrete applied with EMV mix design, which adjusts the mix proportion of concrete based on the physical characteristics of recycled aggregate, is conducted. This single authorship review article demonstrates the competitive performance of EMV-based concrete compared to natural aggregate concrete. A particularly noteworthy finding is that medium- and low-quality recycled aggregates were used to achieve this performance.

Based on these findings, it is hypothesized that the EMV mix design would compensate for the performance loss of concrete due to repeated recycling, and a verification of the hypothesis is conducted in the article [A3]. Unlike the performance of recycled aggregate concrete based on the conventional mix design that deteriorates as the number of recycling cycles increases, the EMV-based concrete at 50% replacement rate shows a similar range of properties during three recycling cycles, while, at 100% replacement rate, the performance of EMV-based concrete gradually decreases, indicating that the adjustment of the material proportion is not a single factor governing the properties of recycled aggregate concrete. In other words, repeated recycling of concrete without loss of performance can be achieved by combining the EMV mix design with an appropriate level of recycled aggregate replacement rate. However, the EMV mix design is limited to recycled aggregate and does not consider the utilization of recycled powder generated during concrete recycling.

Thus, a study on the complete recycling of concrete waste is conducted in article [A4]. Recycled coarse aggregate, recycled fine aggregate, and recycled powder obtained from concrete waste are used to replace coarse aggregate, sand, and cement in concrete, and their effects are investigated. The properties of concrete containing them gradually decrease as the replacement rate increases, regardless of the type of material. However, it has been proven that concrete with these recycled materials is applicable as structural concrete, as it meets the mechanical strength requirements specified by the European standard.

For multi and complete recycling, the effects of recycled powders obtained from three rounds of concrete recycling are investigated in the article [A5]. Concrete with recycled powder gradually deteriorates as its replacement rate and number of recycling increase. However, within a certain range (10%), replacing cement with recycled concrete powder can achieve a similar level (approximately 95%) to concrete without recycled concrete powder, even after being recycled three times. Considering the negative impact of cement on the environment, using recycled powder in concrete, even at a low replacement rate of 10%, provides better cost-value and environmental efficiency. Furthermore, these benefits increase with the number of recycling cycles.

This dissertation makes a crucial contribution by evaluating the impact of repeated recycling on both recycled aggregate and recycled powder obtained from concrete waste. The promising findings, which effectively address the performance degradation of concrete resulting from repeated recycling, broaden the current practice of one-off and partial recycling of concrete waste to multi and complete recycling. In particular, it is worth emphasizing that the methods employed to enhance this performance do not require additional resources (i.e., the use of EMV mix design and adjustment of replacement rate). These methods align with the fundamental purpose of recycling concrete waste, namely environmental protection. In conclusion, the repeated recycling of recycled aggregate and recycled powder based on this approach not only avoids significant compromises in the performance of concrete but also effectively reduces the environmental burden associated with the construction industry.

Based on the limitations of this dissertation, several suggestions for further research can be recommended.

Firstly, future investigations may focus on the combined effect of repeatedly-recycled aggregate and recycled powder. The author claims this research would provide a more comprehensive understanding of the repeated recycling of concrete waste.

Secondly, to enhance the characteristics of recycled powder, it would be beneficial to explore various treatment techniques, such as thermal activation and alkali activation. These treatments can assess the feasibility and potential for high-volume replacement of cement with repeatedly-recycled recycled powder.

Lastly, conducting further research on repeatedly-recycled-reinforced concrete would be valuable for practical applications.

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Scientific achievement

This chapter presents the most significant scientific achievements during the author's PhD period (2019-2023). As of the Web of Science dated June 30, 2023:

- H-index: 6
- Impact factor: 66.853
- MEiN point: 1550
- Non-self-citation: 113

Refereed publications

- **Kim, J.**, Grabiec, A. M., Ubysz, A., Yang, S., & Kim, N. (2023). Influence of mix design on physical, mechanical and durability properties of multi-recycled aggregate concrete. Materials, 16(7), 2744. DOI: 10.3390/ma16072744
  IF: 3.748, MEiN point: 140, Non-self-citation: -.
- **Kim, J.**, & Kim, N. (2023). Exploring the role of thermal activation of cement exposed to the external environment on the improvement of concrete properties. Journal of Materials Research and Technology, 24, 2868-2878. DOI: 10.1016/j.jmrt.2023.03.195
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- **Kim, J.**, Yang, S., & Kim, N. (2023). Effect of plasticizer dosage on properties of multiple recycled aggregate concrete. Journal of Material Cycles and Waste Management, 25(3), 1457-1469. DOI: 10.1007/s10163-023-01624-9
  IF: 3.579, MEiN point: 70, Non-self-citation: -.
- **Kim, J.**, Lee, D., Sičáková, A., & Kim, N. (2023). Utilization of Different Forms of Demolished Clay Brick and Granite Wastes for Better Performance in Cement Composites. Buildings, 13(1), 165. DOI: 10.3390/buildings13010165
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- **Kim, J.**, Grabiec, A. M., & Ubysz, A. (2022). An experimental study on structural concrete containing recycled aggregates and powder from construction and demolition waste. Materials, 15(7), 2458. DOI: 10.3390/ma15072458
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- **Kim, J.** (2022). Influence of quality of recycled aggregates on the mechanical properties of recycled aggregate concretes: An overview. Construction and Building Materials, 328, 127071. DOI: 10.1016/j.conbuildmat.2022.127071
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- **Kim, J.**, & Jang, H. (2022). Closed-loop recycling of C&D waste: Mechanical properties of concrete with the repeatedly recycled C&D powder as partial cement replacement. Journal of Cleaner Production, 343, 130977. DOI: 10.1016/j.jclepro.2022.130977
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- Grabiec, A. M., **Kim, J.**, Ubysz, A., & Bilbao, P. (2021). Some Remarks towards a Better Understanding of the Use of Concrete Recycled Aggregate: A Review. Sustainability, 13(23), 13336. DOI: 10.3390/su132313336
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- Jang, H., **Kim, J.**, & Sicakova, A. (2021). Effect of aggregate size on recycled aggregate concrete under equivalent mortar volume mix design. Applied Sciences, 11(23), 11274. DOI: 10.3390/app112311274
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- **Kim, J.** (2021). Construction and demolition waste management in Korea: Recycled aggregate and its application. Clean Technologies and Environmental Policy, 23, 2223-2234. DOI: 10.1007/s10098-021-02177-x
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- **Kim, J.** (2021). Properties of recycled aggregate concrete designed with equivalent mortar volume mix design. Construction and Building Materials, 301, 124091. DOI: 10.1016/j.conbuildmat.2021.124091

IF: 7.693, MEiN point: 140, Non-self-citation: 16.

Conference papers

- Characteristics of recycled materials from multiple-recycled coarse aggregate concrete, 4th International Conference on Advanced Engineering Technologies, September 28-30, 2022, Bayburt, Turkiye.
- An investigation of the effect of concrete mix design methods on their properties for potential applications as a preventive repair method, ECI and PhD workshop (Cost Action 15202), March 09, 2020, University of Minho, Portugal.
- Towards the understanding the role of the mix design method in the mechanical behaviour of recycled aggregate concrete at early ages, RILEM 2020 Spring Convention, March 10-14, 2020, University of Minho, Portugal.

Research project

- Seeking true sustainability by multiple recycling of thermal-activated waste concrete powder as a partial cement replacement (2023-2025) financed by the National Science Centre, Poland, in the framework of Preludium (21 edition).

Research stay

- Hongik University, Korea (Host: Prof. Sungchul Yang) organized by the NAWA in the framework of the NAWA STER Mobility programme from July 28 to August 27, 2022.
- Technical University of Kosice, Slovakia (Host: Prof. Alena Sicakova) organized by the Ministry of Education, Science, Research and Sport of the Slovak Republic in the framework of National Scholarship Programme of the Slovak Republic from September 15,2022 to March 14, 2023.

Prizes and awards

- Ministerial scholarships for outstanding young scientists (17th edition) awarded by the Ministry of Science and Higher Education, Poland in 2022.
- Wroclaw municipal scholarship (Marian Suski Scholarship) awarded by the Wroclaw Academic Hub in 2021.

Publications

Article [A1]

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Review

Influence of quality of recycled aggregates on the mechanical properties of recycled aggregate concretes: An overview

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ABSTRACT

Considering that a lot of energy is consumed to produce high quality recycled aggregate, efficient use of each quality of recycled aggregate is required. Therefore, this study overviews the literature on the effect of recycled aggregate quality on the mechanical properties of concrete. Some discussion of the characteristics of recycled aggregate and factors affecting the quality of recycled aggregate has been included. Data on the fresh and hardened properties of recycled aggregate concrete mixed with each quality were reviewed. This article can provide insight into the effective utilization of recycled aggregate.

1. Introduction

In many countries, the amount of construction waste generated is increasing every year and it is often reported that concrete waste takes up the largest proportion of the construction waste [1–5]. Except for recycling, construction waste may have options such as landfill, neglect, and dumping. These options negatively impact the environment by causing further depletion of natural resources and disruption of eco-systems [6,7]. Therefore, recycling of concrete waste is essential for the sustainable development of the construction industry.

In the past few decades, extensive research has been conducted on the feasibility of recycling concrete waste by many researchers. As a result of the studies, it is generally agreed that concrete incorporating recycled aggregate (RA) has poorer properties than natural aggregate concrete (NAC). As the RA replacement rate increases, the following changes in concrete properties are observed: decrease in workability [8]; density [9]; permeability [10]; mechanical strength [9,11]; and elastic modulus [12], increase in bleeding [13]; drying shrinkage [14]; and creep deformation [15,16]. These changes in concrete properties can be attributed to the presence of adhered mortar in RA [17–19]. Therefore, continuous efforts have been made to improve the quality of the RA by removing or strengthening the adhered mortar, and to improve the mechanical strength and durability performance of the recycled aggregate concrete (RAC).

According to the review by Tam et al. [20], several countries have established standards for the use of RA, and some of them manage RA by dividing it into high-, medium-, and low quality. The requirements for grading RA include the following tests: water absorption, density, chloride content, impurity content, soundness, LA abrasion. Depending on the RA grade, the RA replacement ratio and purpose of use are limited. For example, according to Hong Kong standard, coarse RA that satisfies the minimum oven-dry (OD) density of 2.0 g/cm^3, the maximum water absorption of 10%, the maximum chloride and sulfate content of 0.04% and 1.0%, respectively, can be substitute NA up to 20% for structural concrete with a compressive strength ranging from 25 MPa to 35 MPa at 28 days. The Italian standard permits the use of 100% RA in non-structural concrete with a 28-day compressive strength of 10 MPa. The Korean standard recommends that the replacement level of coarse RA that satisfies the quality standards for normal strength concrete be within 60% [1].

De Brito et al. [21] emphasized the importance of knowing the properties of aggregates, pointing out that it is unable to accurately estimate the compressive strength of concrete if the properties are ignored. However, the effect of RA quality on the properties of RAC has not been reviewed in much detail. Given that the production of high quality RA requires several processing steps, which takes a lot of time and money [22], understanding the relationship between RA quality and concrete properties can promote efficient utilization of RA. Therefore, this study classifies the quality of RA into four types based on physical characteristics, and discusses factors that affect the RA quality. Furthermore, the effect of RA quality on the properties of RAC is overviewed.

1.1. Research significance and objectives

This study classifies the quality of RA based on characteristics and

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Table 1
Classification of the quality of recycled coarse aggregate on the basis of physical characteristics.

	High quality	Medium quality	Low quality	Nonstandard quality
Reference	[36]	[37]	[38]	n.a
Oven-dry density, g/cm^3	≧ 2.5	≧ 2.3	n.a	n.a
Water absorption, %	≦ 3.0	≦ 5.0	≦ 7.0	≧ 7.0
Applicability [39]	All elements	Mat, pile, etc.	Temporary use only	n.a

investigates the effect of each quality on RAC. The objectives of this study is as follows:

- Identification of factors affecting the quality of RA.
- Overview of the effect of each quality of aggregate on the fresh properties and hardened mechanical properties of concrete.

The findings of this study can provide valuable insight into the efficient utilization of RA of different qualities.

2. Recycled aggregate

2.1. Quality classification

This study begins with the question of how the quality of RA influences the concrete properties. Therefore, the quality class of RA needs to be defined first. Martín-Morales et al. [23] mentioned that the most basic parameters specified in several standards and guidelines for the classification of RA quality are OD density and water absorption. The standards also specify requirements for chloride content, organic content, and alkali-silica reactivity tests, but research papers specifying all these test results are very scarce. In order to establish a more robust knowledge system on the relationship between the various properties of RA and the corresponding RAC, the results of various tests for the properties of RA should be specified in literature. In some studies, RA obtained from high-strength concrete is referred to as high quality, but given that one recycling plant collects and treats concrete waste from various sources, the classification of RA quality based on the strength of the parent concrete may be inefficient from a practical point of view. In addition, the content of adhered mortar is often mentioned as a measure of the RA quality, and a strong correlation between the adhered mortar content and the properties of RAC is observed in the literature [24,25]. However, in this paper, the adhered mortar content is used only as a secondary indicator, not as the main indicator for determining the RA quality for the following reasons: (i) several methods have been proposed for the determination of adhered mortar content [26–28], but there is no internationally standardized method; (ii) the proposed methods do not allow complete removal of adhered mortar [29–32]; (iii) test results of adhered mortar content measurement using different proposed methods for the same aggregate are not similar [33]; (iv) after the end of some of the proposed methods, damage to the original aggregate of RA has been reported [34,35]. Therefore, for these reasons, this paper divides the quality of RA into four categories based on the OD density and 24-hour water absorption. JIS standards are applied to high quality (HRA) [36], medium quality (MRA) [37], and low quality RAs (LRA) [38], and RA that does not meet the requirements for low quality specified in the standard is classified as nonstandard quality (NRA). Table 1 shows the requirements for each grade of RA.

2.2. Characteristics

The most distinctive feature of RA is that it consists of original aggregate and adhered mortar, unlike NA. Due to this adhered mortar, it

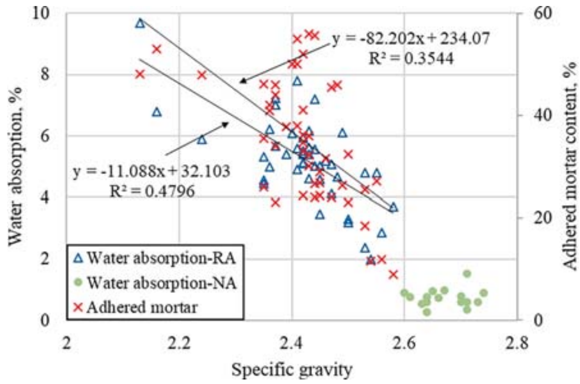

Fig. 1. Physical characteristics of recycled aggregate and natural aggregate [25,31,42–56].

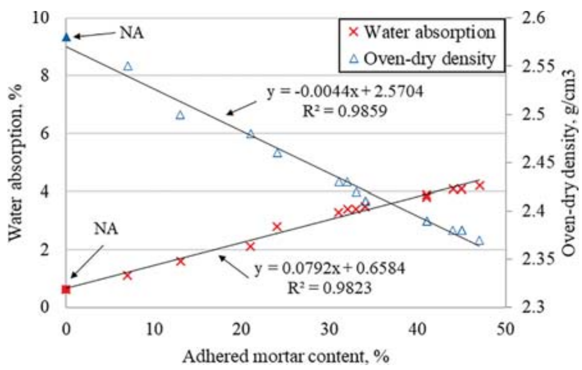

Fig. 2. Correlation among adhered mortar, water absorption and oven-dry density of recycled aggregate [41].

was observed that the porosity of RA measured by mercury intrusion porosimetry was about 6.5 times higher than that of NA [40], and RA is distinguished from NA. Fig. 1 shows the relationship between the water absorption, specific gravity, and adhered mortar content of RA and NA. The specific gravity and water absorption of NA are in the range of 2.6–2.7 and 0.5–1.8%, respectively, while those of RA are in the range of 2.1–2.58 and 2–10%. The adhered mortar content shows a tendency to be proportional to water absorption and inversely proportional to specific gravity. From an overall point of view, the coefficient of determination (R^2) for the relationship between specific gravity and adhered mortar content is not high. However, this may be due to the fact that, as mentioned in the previous section, there is no standardized method for determining the adhered mortar content, and the mortar removal efficiency for the presented methods is different. Akbarnezhad et al. [41] investigated the characteristics of RA obtained from the same source of concrete, and found that there was a very strong correlation among the adhered mortar, water absorption and OD density (Fig. 2). The R^2 value for each correlation was over 0.98.

RA can be divided into 'mortar-attached aggregate' and 'mortar-covered aggregate' depending on the shape and degree of adhered mortar to the original aggregate [57]. However, it is impossible to visually determine whether there is original aggregate inside RA covered with mortar. Therefore, the mortar-covered RA can be subdivided into 'RA in which mortar covers aggregate' and 'RA with no original aggregate' (Fig. 3). The latter is equivalent to 100% of the adhered mortar content. Considering that the mortar is a porous material, when the original aggregate is the same, the water absorption capacity of 'mortar-attached RA' would be lower than that of 'mortar-

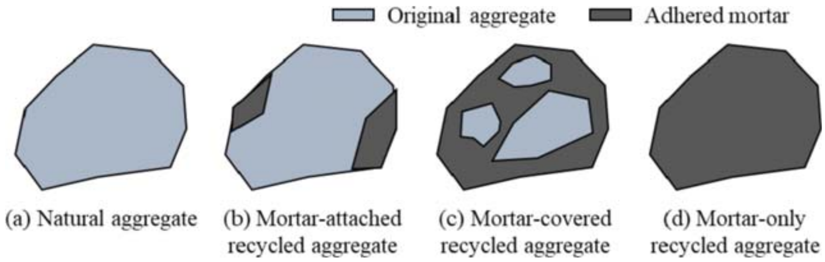

Fig. 3. Types of aggregates depending on adhered mortar.

Table 2
Various production methods and physical characteristics of recycled aggregate produced therefrom [66].

Method	Description	Oven-dry density, g/cm^3	Water absorption, %
Heat and rubbing	Concrete debris is put into a countercurrent rotary kiln and heated to about 300 ℃ to weaken the mortar paste, and then grounded by a uniaxial horizontal hammer mill.	2.56	1.91
Eccentric rotary grinding	Concrete waste is fed through the gap between the outer and inner cylinders, rotated and crushed at high speed to remove the mortar.	2.59	1.83
Screw grinding	Concrete rubble is put into a rotating cylindrical vessel with a horizontal axis and a discharge cone, and compressed and crushed by a rotating screw.	2.54	2.26
Rotary drum mill	Concrete debris is fed into a rotating cylindrical vessel with rotary rollers and drum mills, and crushed by the pressure-controlled rollers.	2.59	1.36
Natural aggregate	–	2.62	0.72

covered RA', and the 'mortar-covered RA' would have lower absorption than 'mortar-only RA'. Density can be expected to have the opposite tendency to absorption.

2.3. Effect of the production process on recycled aggregate quality

Equipment, number of crushing, and technologies for producing RA from concrete waste are factors directly related to the RA quality [58,59]. Seemingly, the most widely used method in RA production is multiple crushing using crushers based on friction, impact and compression forces and so on. In general, as the number of crushing increases, the density of RA increases and the water absorption decreases [60]. Choi et al. [61] reported that it was possible to mass-produce RA with a fraction of 5 mm to 10 mm, which satisfies the requirements for high quality, by crushing it three times with a cone crusher. Increasing the number of crushing can improve the RA quality, but conversely lower the recovery rate of RA [62]. Nagataki et al. [63] found that the proportion of coarse RA produced in 1-ton concrete decreased from 60% to 45% and 35% with the increasing number of treatments.

Combinations of various methods are also proposed to improve the RA quality by removing adhered mortar. Koshiro and Ichise [64] recovered HRA from concrete waste using the heating and grinding method. The concrete mass is placed in a rotary kiln at 250 ℃, processed twice on two slanted rotary grinders connected in series, and then separated by size. The quality of the RA produced through this method

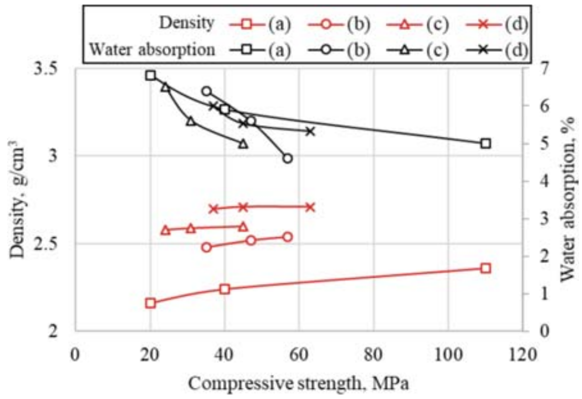

Fig. 4. Effect of compressive strength of parent concrete on the physical characteristics of recycled aggregate (a) [48]; (b) [75]; (c) [76]; (d) [77].

satisfied the standards for HRA with an OD density of 2.59 g/cm^3 and water absorption of 1.38%. Kim et al. [65] improved the RA quality through ball milling in sulfuric acid solution. Table 2 shows various RA production methods and the physical characteristics of RAs produced by each method investigated by Hideo et al. [66]. The same concrete samples were used for the methods. As shown in Table 2, the RA quality depends on the production process, but HRA can be produced using various technologies. Yoda and Shintani [39] actually stated that many techniques have been developed for the production of HRA.

In addition, the following techniques for improving the RA quality have been reported: electric pulsed power method [67]; acid, ball milling [68]; microorganism [69]; RA carbonation [70]. However, some methods give rise to economic and ecological issues due to the need for special mechanical equipment, increased energy consumption and processing time [71]. For instance, technologies using acidic solutions must take into account issues such as the safety and disposal of solutions and wash water [72]. Furthermore, methods that use thermal energy releases additional CO_2. Mechanical crushing methods show CO_2 emissions of 1.5 to 4.5 $kgCO_2$/t, whereas heating methods using rotary kilns or kerosene emit around 200 $kgCO_2$/t [73]. Therefore, methods that can produce RA of acceptable quality with little impact on the environment need to be discussed. In this context, the importance of the influence of RA quality on concrete properties is worth mentioning once again.

2.4. Effect of the strength of parent concrete on recycled aggregate quality

The strength of the parent concrete is one of several parameters that affect the RA quality. Katz [74] noted that the difference between the quality of new and old cement matrices attached to RA seems to be the main parameter governing the properties of RAC. Fig. 4 shows the relationship between the compressive strength of the parent concretes and the physical characteristics of RAs produced from the parent

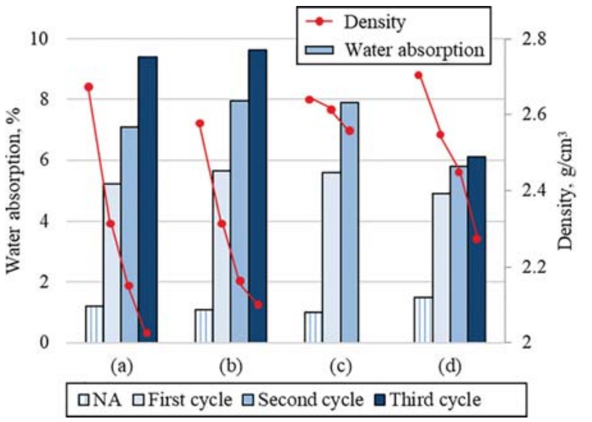

Fig. 5. Effect of multiple uses of recycled aggregates on their quality (a) [87]; (b) [88]; (c) [89]; (d) [90].

concretes.

Gholampour and Ozbakkaloglu [48] produced concretes with different compressive strengths of 20 MPa, 40 and 110 MPa using NA with known physical properties such as density and water absorption, and crushed them to obtain RAs and evaluated the physical properties. The density and water absorption of the RA obtained from the parent concrete with a compressive strength of 20 MPa were 2.16 g/cm^3 and 6.8%, respectively, and were classified as LRA. The density and water absorption of the RA from the concrete with a compressive strength of 40 MPa were 2.24 g/cm^3 and 5.9%, which was also LRA. While, for concrete with compressive strength of 110 MPa, the density and water absorption were 2.36 g/cm^3 and 5%, respectively, thus, the RA was classified as MRA. Similarly, Liu et al. [75] produced three NAC having different compressive strengths of 35 MPa, 47 MPa, and 57 MPa using the same NA. The NACs were crushed to obtain three RAs and their physical properties were investigated. Compared with the RA obtained from the NAC with a compressive strength of 35 MPa, the density of the RAs obtained at 47 MPa and 57 MPa was 1.6% and 2.4% higher, respectively, while the water absorption was 12% and 28% lower. This trend can be found in different publications [76–78]. Therefore, a close relation is observed between the quality of parent concrete and RA produced therefrom, and assuming that the same crushing method is applied, the quality of RA obtained from high strength concrete is higher than that of the RA obtained from low strength concrete. This may be due to the low water-to-cement (w/c) ratio used to make the high strength concrete. Reduction of the w/c ratio decreases the capillary porosity of the cement paste [79,80], and makes the microstructure of the cementitious composites denser [81,82]. It is worth mentioning that each of the studies abovementioned produced parent concrete with different strengths using the same NA. This is because the correlation between properties of parent concrete and RA cannot be directly compared if parent concrete is manufactured with different NAs or collected from different sources.

An opposite trend was reported by Rao [83] and Padmini et al. [84]. As the strength of the parent concrete increased, the density of RA decreased and the water absorption increased. In low strength concrete, which has relatively weak bonding strength between mortar paste and original aggregate compared to high strength concrete, most of the adhered mortar is separated from the original aggregate during the crushing process. Therefore, the authors noted that the amount of adhered mortar of RA obtained from low strength concrete was lower. In addition, the separated adhered mortar is incorporated into the RA of the small fraction during the screening process, which explains that the RA in the small fraction has a higher adhered mortar content than in the large fraction.

2.5. Effect of the repeated use of recycled aggregate on recycled aggregate quality

Since RA is already used in concrete structures on a real scale [1,85,86], it is necessary to investigate the effect of the number of uses of RA on the quality of the next-generation RA.

In some studies [87–90], effects of multiple uses of RA for concrete on RA quality have been observed. For example, Huda and Alam [87] produced 100% RAC with RA (i.e 1st generation) and obtained 2nd generation RA after 56 days of curing. Using the 2nd generation RA, 100% RAC was produced, cured for 56 days, and then crushed and sorted again to produce 3rd generation RA. Then, the physical properties of RA for each generation were assessed. Fig. 5 shows the density and water absorption of RA with the number of repetitions. In general, as the number of repetitions increases, the water absorption and crushing index significantly increase, and the density decreases. In addition, Thomas et al. and Zhu et al. [91,92] observed that the adhered mortar content increased proportionally with the number of RA uses. When crushed with a laboratory crusher without additional treatment, NA has become LRA with the water absorption exceeding 5% in just one use. In particular, when RA is reused, it appears to have poor quality that does not even meet the requirements of LRA. Therefore, in order to use RA several times, the application of various technologies for quality improvement may have to be considered. With respect to the number of repeated use of RA, Thomas et al. [91] confirmed that a larger number of cracks and interfaces existed as the RA was reused. In addition, it was mentioned that the adhered mortar content was more than 80% when recycled three times, and RA will consist only of mortar from the fourth use.

3. Recycled aggregate concrete

3.1. Fresh properties

3.1.1. Workability

The slump test is mainly used to measure the workability of concrete in the fresh state [93,94]. Cho et al. [95] further processed HRA (HRA1 with OD density of 2.54 g/cm^3 and water absorption of 2.26%) to produce better HRA (HRA2 with OD density of 2.58 g/cm^3 and water absorption of 1.82 %). In the slump test of RACs made with these HRAs (HRAC1 and HRAC2), the slump value of HRAC1 slightly decreased from 90 mm to 80 mm, while the slump of the HRAC2 was increased to 110 mm. The admixture, w/c ratio, and raw material amount of each mixture were the same. Tijani et al. [96] produced concrete using NRA (NRAC) without chemical admixture with a density of 2.16 g/cm^3 and water absorption of 7.65%. At RA replacement ratios of 25%, 50%, 75%, and 100%, the slump tended to decrease to 95 mm, 80 mm, 75 mm, and 70 mm. Although a tendency to decrease the slump with the increase of RA replacement level is observed in the literature [97,98], unlike the mechanical performance of concrete, which will be discussed in later sections, the slump of RAC seems difficult to interpret with RA replacement ratio and quality. Ismail and Ramli [99] improved the quality of RA (i.e. increased density and decreased water absorption) by removing the adhered mortar with an acid solution. However, the authors reported that no clear relationship was found in the slumps between the RACs made with untreated RA and the quality-improved RA by acid treatment.

The moisture state of RA is a major parameter that affects the workability of concrete mixtures. RA in the saturated surface-dried (SSD) state contains moisture in the adhered mortar pores, increasing the unit water content of concrete. This reduces the yield stress of the mixture, resulting in a high slump value [100]. Similarly, Yang and Kim [101] used RA in the SSD state for concrete mixing. The replacement ratios were 30%, 50%, 70%, and 100%, and the same w/c ratio was applied for all mixture series. In other words, it can be seen that the actual w/c ratio of concrete increased as the replacement ratio increased

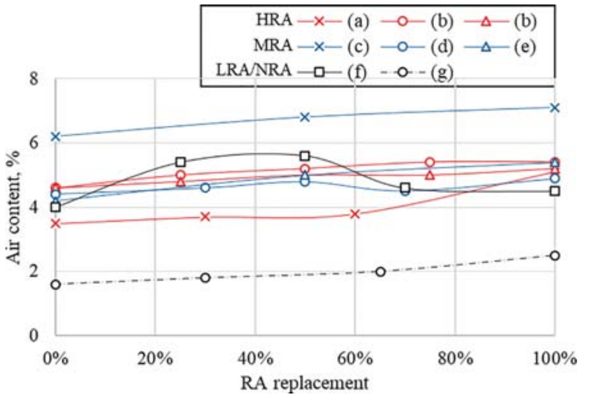

Fig. 6. Effect of recycled aggregate quality on the air content of recycled aggregate concrete (a) [110]; (b) [95]; (c) [111]; (d) [101]; (e) [112]; (f) [108]; (g) [102].

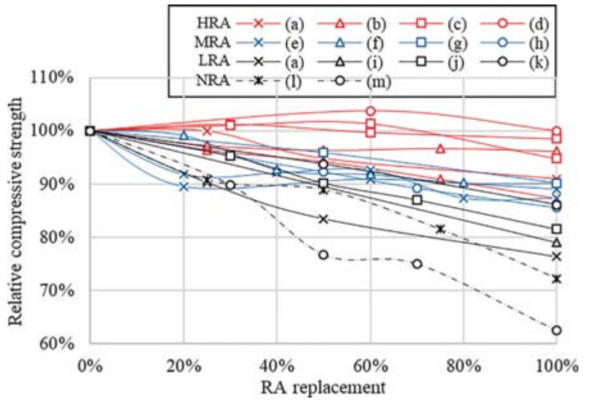

Fig. 7. Effect of recycled aggregate quality on the compressive strength of recycled aggregate concrete (a) [17]; (b) [95]; (c) [110]; (d) [113]; (e) [106]; (f) [114]; (g) [111]; (h) [101]; (i) [115]; (j) [116]; (k) [14]; (l) [96]; (m) [117].

due to moisture in the pores of the adhered mortar. The slump measured in the study was in the range of 93–109% compared to that of NAC regardless of the replacement level. Alternatively, the slump can be increased by adding water during the concrete mixing process. Wardeh et al. [102] reported that it was able to maintain a constant slump value (180 ± 10 mm) despite the increase in the RA replacement rates of 30%, 65% and 100% by adding additional mixing water to the oven-dried NRA concrete during the mixing process. However, compared to aggregates in the SSD and the air-dried states, concrete with RA in the OD state rapidly decreases the amount of free water in the mixture due to water absorption by the dry RA, which leads to a quicker loss of slump with time [40].

The workability of RAC is influenced by RA texture and shape [103]. In the study performed by Butler et al. [30], RAC required 3.1–9.4% additional mixing water to achieve similar levels of workability as NAC. The authors attributed this to the increased intergranular friction due to the more angular shape and the roughened surface texture of RA. On the contrary, in another study [104], in which round shape RA was used, the percentage of superplasticizer required to achieve the concrete slump of 150 ± 25 mm at RA replacement ratios of 10%, 30%, and 50% was reduced from 0.6% (for NAC) to 0.5%, 0.45%, and 0.4%. This is because the round shape aggregate particles tend to increase the workability of concrete due to the ball-bearing effect [105]. However, it has been often reported that it is possible to achieve a target slump irrespective of the RA quality and replacement ratio by using chemical additives and the pre-wetting method [106–108].

3.1.2. *Air content*

Considering the characteristics of RA, which is more porous than NA, the replacement rate and quality of RA can be expected as a factor in increasing the air content. Lee et al. [109] reported that the air content increased as the RA quality decreased by using three RAs with different absorption capacities and densities.

Fig. 6 shows the air content of concrete mixtures using HRA [59,110], MRA [101,111,112], LRA [108] and NRA [102]. In all quality, an increase in air content is commonly observed with an increase in replacement level, and the difference between the minimum and maximum air contents is controlled up to 1.5%. In this context, Silva et al. [94], reviewing the fresh state properties of RAC, concluded that many studies show an increase in air content with increasing RA replacement levels, but in almost all cases, these variations are of no practical significance.

3.2. *Hardened properties*

3.2.1. *Compressive strength*

Compressive strength is the most basic and representative property that is the basis of other properties such as mechanical strength and durability of concrete. Fig. 7 shows the relative compressive strength of concretes made with each quality of RA as a function of the replacement levels.

Kim et al. [31] obtained HRA (OD density of 2.5 g/cm^3 and water absorption of 2.87%) and LRA (OD density of 2.26 g/cm^3, water absorption of 6.07%) from the same source of concrete waste by applying different crushing techniques, and RAC were produced respectively with two RAs (HRAC and LRAC). At replacement ratios of 25%, 50% and 100%, the compressive strength of HRAC was 30.9 MPa, 29.3 MPa, and 28.1 MPa, which was 0, 5%, and 9% lower than that of NAC. While, the compressive strength of LRAC decreased by 10%, 17%, and 24%, indicating that there is a strong correlation between the RA quality and the compressive strength of concrete. Cho et al. [95] further processed HRA1 with an OD density of 2.54 g/cm^3 and water absorption of 2.26% to obtain HRA2 with an OD density of 2.58 g/cm^3 and water absorption of 1.52%. According to the standard, both of these RAs fall into the category of high-quality, but it is clear that HRA2 is of higher quality. Therefore, as expected, at a replacement level of 100%, HRAC1 reduced the compressive strength by about 13% compared to that of NAC, whereas that of HRAC2 decreased by about 4%. A similar trend is observed in another study [110,113].

For concrete with MRA (MRAC), the decrease in compressive strength with increasing replacement level appears to be greater than that of HRAC. Hamad and Dawi [106] made two MRACs and measured the compressive strength. The decrease in compressive strength observed in their study was 92% and 87% at replacement levels of 60% and 100%, respectively. Talamona and Hai Tan [114] also showed relative compressive strengths of 92% and 90% at the same replacement ratios. Similar compressive strength behavior with increasing replacement level is observed in the literature [101,111]. In the studies using LRA [14,31,115,116], the compressive strength of LRACs decreased to 76–86% of that of NAC at 100% RA replacement rate.

The use of RA that does not meet the standard results in a greater reduction in compressive strength [96]. The compressive strength of NRAC using NRA with an OD density of 2.18 g/cm^3 and water absorption of 8.01% was dropped by about 10%, 23%, and 37% compared to NAC at replacement ratios of 30%, 50%, and 100% [117].

Fig. 7 represents the general agreement that the compressive strength of RAC decreases as RA replacement rate increases, but HRA with a low adhered mortar content does not appear to have a significant

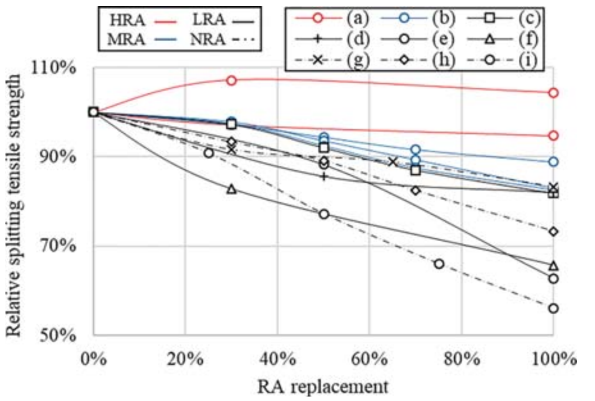

Fig. 8. Effect of recycled aggregate quality on the splitting tensile strength of recycled aggregate concrete (a) [113]; (b, c) [101]; (d) [14]; (e) [122]; (f) [121]; (g) [102]; (h) [117]; (i) [96].

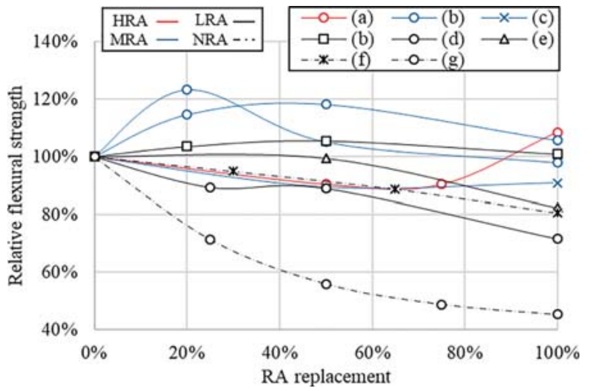

Fig. 9. Effect of recycled aggregate quality on the flexural strength of recycled aggregate concrete (a) [123]; (b) [118]; (c) [112]; (d) [124]; (e) [122]; (f) [102]; (g) [96].

effect on the compressive strength of concrete as the replacement rate increases. This may be due to the fact that HRA requires similar or the same level of physical properties as NA. In general, when the quality of RA is lowered, the decrease in compressive strength is observed to be greater as the replacement rate increases. However, MRAC can exhibit about 90% of the performance of NAC at 100% replacement level. For LRAC and NRAC, about 90% of the compressive strength of NAC can be achieved at a replacement rate of 30%. Thus, the RA replacement ratio needs to be considered depending on the RA quality. Furthermore, although variations in compressive strength are observed depending on the RA quality, Butler et al. [30] found that the target compressive strength can be achieved even if LRA is used. In that study, the compressive strengths of RACs using MRA and LRA were 44 MPa and 37 MPa, respectively, exceeding the target strength of 30 MPa.

The compressive strength of RAC is associated not only with the RA quality but also to the property of the parent concrete. Andreu and Miren [118] produced three RACs made with RAs obtained from concretes with different compressive strengths of 40 MPa, 60 MPa, and 100 MPa, respectively. The obtained RAs were LRA and two MRAs, and the replacement rates were 20%, 50%, and 100%. For LRAC using LRA obtained from 40 MPa concrete, the compressive strength was reduced up to 89% compared to that of NAC, and the compressive strength of MRAC made with MRA from 60 MPa parent concrete ranged from 99% to 101% at each substitution level. MRAC made MRA produced from 100 MPa parent concrete had strengths in the range of 103–106%. This may be attributed to the higher strength of RA produced from high-strength parent concrete [119]. It has been reported that the interfacial transition zone (ITZ) between the original aggregate and the adhered mortar of RA produced from high-strength concrete is stronger than that of RA from low-strength concrete. Another possible reason is that the adhered mortar contains unhydrated cement, which contributes to an increase in strength [74]. Padmini et al. [84] reported that the adhered mortar in HRA contained large amounts of silicon and aluminum, resulting in further hydration of sulfate ions in the aluminate phase within RA.

3.2.2. *Tensile and flexural strength*

Concrete containing RA obviously tends to have lower tensile strength than NAC, but in some cases, RAC has comparable or slightly higher strength [120]. This trend can be explained in relation to the RA quality.

Less variations in the strength of concrete are favorable for quality control. Concrete mixed with HRA can exhibit similar performance to NAC in terms of tensile strength regardless of the replacement rate. In the study conducted by Jang et al. [113], the tensile strength of two series of HRACs at 30% replacement rate was in the range of 97–107% than that of NAC, and at 100% replacement level, the tensile strength was reduced by 2% and 3% to 95% and 104%. As expected, compared to HRAC, the relative strength reduction of MRAC is slightly greater. In the study [101], the tensile strength of MRAC with three different w/c ratios (0.53, 0.46, 0.36) was about 1% and 6% lower than that of NAC at 30% and 50% replacement ratios, respectively, and at 100% replacement, a decrease in strength was approximately 11–17%. Although the decrease in strength with increasing RA replacement rate seems inevitable, the MRA can achieve approximately 95% of the tensile strength of NAC at 50% RA replacement rate.

In some studies [14,102,116], NRAC and LRAC showed similar behavior to MRAC, whereas the tensile strength of LRAC and NRAC used in other studies [96,117,121,122] fell by 27–46% at 100% replacement. Yang and Jeong [116] stated that the splitting tensile strength did not show a significant decrease compared to NAC within the range of the RA replacement rate of up to 30%. Bui et al. [117] also noted that the decrease in tensile strength with increasing RA replacement ratio is not as pronounced as that of compressive strength. However, as can be seen from Fig. 8, there appears to be a correlation between the RA quality and the tensile strength of concrete from a macroscopic point of view.

In the case of flexural strength of concrete, Wardeh et al. [102] reported that the flexural strength of NRAC gradually decreased by up to 20% as the replacement rate increased. This can be reduced by up to 65% [96]. However, with a few exceptions, no appreciable trend is observed between flexural strength and RA quality, unlike compressive strength and tensile strength. Fig. 9 shows the relative flexural strength as a function of the RA incorporation rate. In the study using HRA [123], the flexural strength of HRAC at 50% and 75% RA replacement levels was about 90% of that of NAC, but at 100% replacement ratio, the relative flexural strength was about 110%, showing a sudden improvement. According to the study by Andreu and Miren [118], RAs obtained from different strength concretes (40 MPa, 60 MPa and 100 MPa) were of LRA, MRA and MRA, respectively, but the 7-day flexural strength at 100% RA replacement rate was 6.53 MPa, 6.33 MPa, 6.84 MPa, which were similar to that of NAC, 6.47 MPa. In this regard, the authors noted that the flexural strength appears to be less affected by the RA quality or the replacement rate.

Some researchers have reported that the flexural strength of RAC depends on the surface properties of RA rather than the degree of substitution of RA. The texture of RA is rough due to the presence of the adhered mortar, which has a positive effect on the flexural strength of RAC [125]. Also, Kou et al. [126] reported that RA significantly improved the long-term interfacial properties of RAC due to the long-term self-cementing effects of the adhered mortar and the interaction of the adhered mortar with the new mortar. However, more research

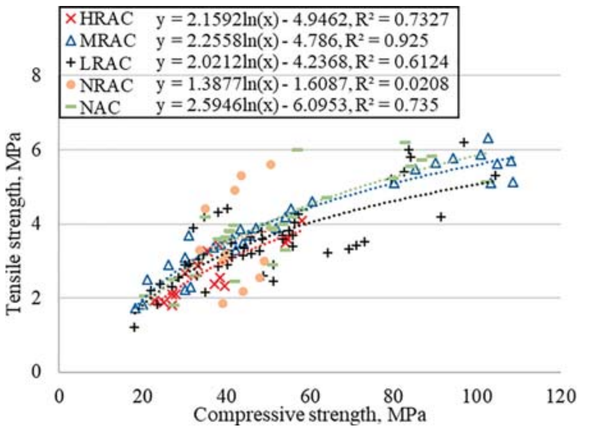

Fig. 10. Relationship between compressive strength and tensile strength of concrete with different aggregate quality.

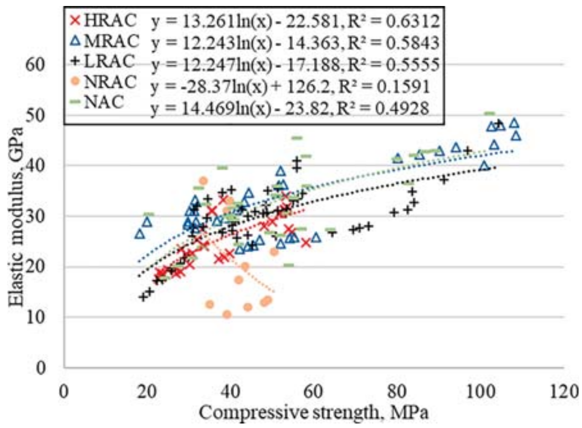

Fig. 12. Relationship between compressive strength and elastic modulus of concrete with different aggregate quality.

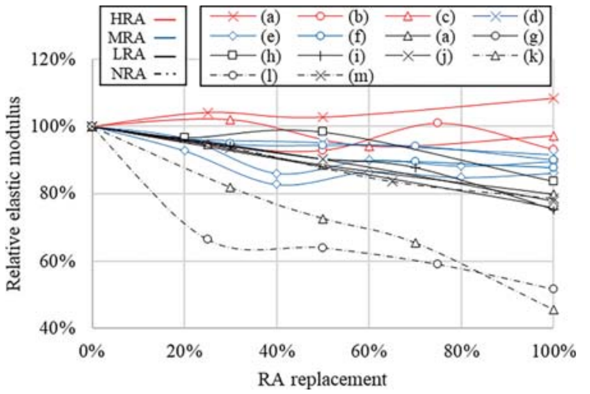

Fig. 11. Effect of recycled aggregate quality on the flexural strength of recycled aggregate concrete (a) [17]; (b) [95]; (c) [113]; (d) [118]; (e) [106]; (f) [101]; (g) [130]; (h) [107]; (i) [116]; (j) [14]; (k) [117]; (l) [96]; (m) [102].

data are needed to clearly explain the relationship between RA quality and flexural strength of RAC.

Fig. 10 shows the relationship between compressive strength and tensile strength of concrete with different qualities of RA extracted from different literature [14,31,48,96,101,102,106,107,116–118,121–124,127–130]. Except for NRAC, this relationship showed a significant or strong coefficient of determination of 0.6124–0.925. Because NRAC shows a very low correlation with an R^2 value of 0.02, the properties can be difficult to predict when using RA of out-of-range quality. From a macroscopic point of view, the relationship between compressive strength and tensile strength at normal and medium strength (up to 60 MPa) was similar regardless of RAC and NAC, which is in line with that reviewed by Silva et al. [120]. However, since the trend line of HRAC is lower than that of MRAC, LRAC, and NAC, it was found that the tensile strength of HRAC is lower than that of concrete made of other quality aggregates at the same compressive strength level. This can be associated with RA shapes and textures. As previously described, the roughness and shape of RA are parameters that affect the tensile strength of RAC. MRA and LRA contain a higher amount of adhered mortar than HRA, which tends to make RA more angular [131]. In other words, with a small amount of adhered mortar, HRA has a more rounded shape compared to other quality RAs, which may be unfavorable to tensile strength. Obviously, more data are needed to predict the relationship between tensile strength and compressive strength in ultra high strength concrete, and in particular, not many studies have been conducted on HRAC.

3.2.3. Elastic modulus

The elastic modulus is one of the major mechanical properties that indicate the stiffness of concrete [132]. When NA is replaced with RA, the elastic modulus is generally reduced. Xiao et al. [11] noted that the elastic modulus decreased by 45% at 100% RA replacement ratio, and Dimitriou et al. [54] reported a reduction of 12–33% at the same replacement level. These losses are attributed to the fact that the increase in RA content adversely affects the elastic modulus due to low density, porous nature and the weak bond between old and new ITZ caused by more capillary pores and cracks in RA [133]. Hence, it can be expected that HRA with low adhered mortar content has less effect on the elastic modulus of elasticity of RAC than other qualities of RA.

Relative elastic modulus as a function of RA replacement levels is shown in Fig. 11. According to the study [17] using HRA and LRA obtained from the same source of concrete waste, the elastic modulus of HRAC was 22.7 GPa, 22.4 GPa, 23.6 GPa at the replacement ratios of 25%, 50%, and 100%, whereas that of LRAC showed 20.6 GPa, 19.3 GPa, and 17.4 GPa, showing a greater decrease. Similarly, in the literature [95,113] in which HRA was used, a gradual decrease in the elastic modulus was observed as the replacement ratio increased, and the loss percentage at 100% replacement ratio was 3–17% compared to the control group (i.e. NAC). In comparison with HRAC, a slightly greater modulus loss is observed in MRAC. The elastic modulus reduced by 10–20% at 100% replacement ratio compared to NAC has been reported in the literature [101,106,118]. For LRAC, the reduction goes up to 16–26% [14,107,116,130]. Predictably, concretes mixed with NRA had a greater loss of modulus than concrete with other quality of RAs. Tijani et al. [96] observed a decrease in the elastic modulus of about 33% compared to NAC at 25% RA replacement. According to some studies [96,102,117], the elastic modulus of NRAC fell by 22–55%.

As expected, it can be seen that the use of HRA did not have a significant effect on the decrease in the elastic modulus as the replacement rate increased. However, in some cases, the RA quality is not associated with the significant loss of elastic modulus. In some studies [108,124,134,135], a loss of 7–14% in the elastic modulus was observed at 100% LRA replacement. This is because, like other properties of RAC, the RA quality is not the sole parameter that affects the elastic modulus. Fundamentally, the characteristics of the aggregates, the cementitious materials used, and the mix designs used in each study are different.

As with compressive strength, the elastic modulus of RAC is influenced by the properties of the parent concrete. Andreu and Miren [118]

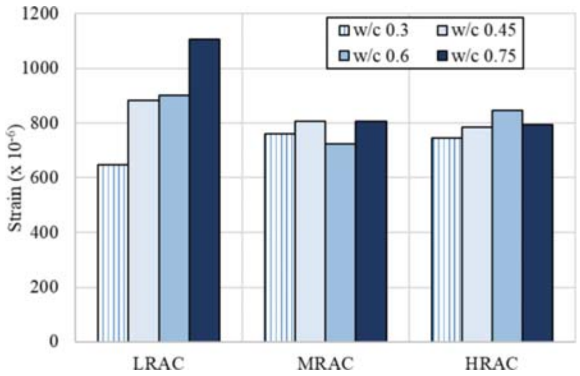

Fig. 13. Effect of recycled aggregate quality on the drying shrinkage of recycled aggregate concrete [139].

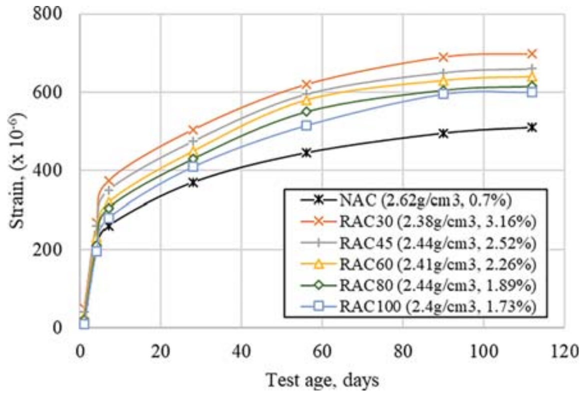

Fig. 14. Effect of compressive strength of parent concrete on the drying shrinkage of recycled aggregate concrete [119].

produced NACs with three different compressive strengths of 40 MPa, 60 MPa, and 100 MPa using one type of NA, and obtained RAs from each NAC by crushing them after curing. Using the three RAs obtained, each RAC was fabricated and the elastic modulus was evaluated. The elastic modulus of the RACs made from RAs crushed from 40 MPa, 60 MPa, and 100 MPa parent concretes were 37.2 GPa, 40.1 GPa, and 46.1 GPa, respectively. Gholampour and Ozbakkaloglu [48] also found that the elastic modulus of concrete made with RA from high-strength parent concrete (i.e. 110 MPa) was about 30% and 9% higher than those of concrete made from RAs produced from parent concrete with compressive strength of 20 MPa and 40 MPa.

Fig. 12 plots the relationship between compressive strength and elastic modulus of RAC with different RA qualities [14,31,48,95,96,101,102,106,107,113,116–118,123,124,127,129,130,134,135]. The coefficient of determination between the two properties ranged from 0.159 to 0.631, and the value increased as the quality of RA improved. Hence, the use of good quality RA can make the elastic modulus of concrete more predictable based on its compressive strength. Moreover, these findings justify the need for securing the appropriate quality of RA.

3.2.4. Drying shrinkage

There are several types of shrinkage, such as drying shrinkage, autogenous shrinkage, and plastic shrinkage, but among them, drying shrinkage can be considered the most significant part [136]. Shrinkage is caused by water loss by evaporation, hydration or carbonation of cement [137], and at the same mixture proportioning, the drying shrinkage strain of RAC is greater than that of NAC [138]. This is due to the fact that when the amount of adhered mortar of RA is increased, the stiffness of the RA is lowered and thus the resistance to deformation is reduced [88].

Yanweerasak et al. [139] fabricated RACs at water-cement ratios of 0.3, 0.45, 0.6, and 0.75 using HRA, MRA and LRA, respectively, and measured the drying shrinkage deformation (Fig. 13). An increase in drying shrinkage strain with increasing w/c ratio was commonly observed in aggregates of each quality, but the degree of shrinkage was particularly high in LRAC. Compared with MRAC and HRAC, the shrinkage strain of LRAC is the largest in all w/c ratios except for LRAC at a w/c ratio of 0.3. HRAC has a slightly smaller shrinkage than MRAC except for the water-cement ratio of 0.6, but the difference between the two groups is not significant. Similarly, in the study [111], the drying shrinkage of MRAC with a target strength of 21 MPa was 38% higher than that of NAC, whereas, for MRACs with medium and high target strength of 35 MPa and 50 MPa, the length change was about 15% to 17%. In other words, a low w/c ratio (i.e. high-strength concrete) can mitigate the drying shrinkage deformation [77]. Ozbakkaloglu et al. [124] reported that normal-strength concrete exhibits higher shrinkage than high-strength concrete at the late stage of curing, due to the presence of a greater amount of residual water in concrete structure.

The strength of the parent concrete is a factor influencing the drying shrinkage of RAC. The effect of the strength of the parent concrete on the drying shrinkage of RAC can be found in the study [119]. Fig. 14 shows the relationship between the strength of the parent concrete and the drying shrinkage. In Fig. 14, RAC30 denotes concrete made with RA obtained from parent concrete with a compressive strength of 30 MPa, next to it, the density and water absorption of RA are indicated. All RAC series showed higher drying shrinkage than NAC, but as the strength of the parent concrete increased, the drying shrinkage tended to decrease. Similarly, in the study [140], the drying shrinkage of RACs produced from parent concrete with compressive strengths of 40 MPa and 60 MPa were 57–172% and 50–113% higher than that of NAC, respectively, but that of RAC produced from 100 MPa parent concrete increased only by 54–56%. These results are also observed in the literature [48]. Commonly, in these papers, RAs obtained from high-strength parent concrete showed better quality characteristics than those obtained from low-strength parent concrete. This supports the review in the previous section that the strength of the parent concrete is an influencing factor of the RA quality.

4. Conclusions

Landfilling construction waste not only causes landfill shortages and environmental problems, but also wastes usable resources. Also, indiscriminate production of HRA can lead to additional waste of energy. In this context, a review of the relationship between RA quality and RAC properties is a possibility and a necessity to further improve the sustainable development in the construction industry through the effective use of concrete waste. This paper can be helpful to formulate guidelines for RCA, and the conclusions can be drawn as follows:.

- The quality of RA is influenced by the production process, the strength of the parent concrete and the number of uses.
- With respect to the fresh state properties of RAC, workability seems to be more influenced by the granularity of RA and the chemical admixture rather than the RA quality.
- The RA quality affects the mechanical properties and durability of RAC, and the performance of RAC deteriorates when the RA quality is low or the replacement rate increases. However, the deterioration degree of RAC is relatively insignificant when using HRA irrespective of the replacement ratio. For LRAC, in many cases, within 30% of RA replacement can achieve about 90% performance compared to NAC. Therefore, for more efficient utilization, it is suggested to adjust the RA replacement ratio based on its quality.

- Except for NRA, the relationship between compressive strength and tensile strength, and the compressive strength and elastic modulus, showed similar behavior to NAC in normal strength concrete (up to 40 MPa), thus, tensile strength and elastic modulus can be predictable based on the compressive strength of RAC.
- RAC incorporating RA obtained from high-strength parent concrete shows better performance than RAC made from RA obtained from medium- and normal-strength parent concrete. Therefore, if possible, the investigation of the strength of the parent concrete needs to be considered.
- Given that HRA production requires higher manufacturing energy, it can be more energy-friendly to use MRA or LRA at low replacement ratios.

RAC have a highly complex structure, and the structure varies depending on the w/c ratio, chloride exposure, cementitious materials and admixtures used, properties of parent concrete and original aggregate. Thus, data from different studies cited in this paper are not comparable to each other. There were also fewer than expected papers presenting OD density of RA which is used for quality classification in various standards. Therefore, the effect of RA quality on some properties such as flexural strength could not be clearly concluded. For a better understanding of RA quality for concrete performance, the following recommendations are suggested:.

- More information on the properties of RA should be written in the research article. This will be helpful in the future discovery of other parameters affecting the properties of RAC.
- More research data on concrete using HRA need to be accumulated. This can lead to a clearer understanding of how the RA quality affects concrete properties.
- Various studies based on the RA quality should be conducted. This includes ultra-high strength concrete, durability, microstructural analysis.

Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Review

Properties of recycled aggregate concrete designed with equivalent mortar volume mix design

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HIGHLIGHTS

- Effect of the equivalent mortar volume (EMV) mix design is discussed.
- The EMV method improves the properties of recycled aggregate concrete.
- The use of EMV method leads to savings in raw materials.
- Environmental pollution can be mitigated with the EMV mix design.

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ABSTRACT

Due to the adhered mortar attached to recycled aggregate, the volume of mortar in recycled aggregate concrete is larger than that of natural aggregate concrete, while the volume of aggregate is smaller. Changes in the ratio of the raw materials constituting concrete may be responsible for the deterioration of the properties of recycled aggregate concrete, but it can be controlled by the equivalent mortar volume mix design method, which considers the adhered mortar in recycled aggregate as a mortar rather than an aggregate. Therefore, this paper provides a literature review on the properties of recycled aggregate concrete designed by the equivalent mortar volume method, which is one of the novel mix designs for recycled aggregate concrete. Starting with the fresh properties such as slump, density, and air content of concrete, the mechanical properties and durability performance of hardened concrete are discussed. It also provides insight into the environmental benefits of the mix design.

Contents

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1. Introduction

Concrete and asphalt waste account for a large portion of construction waste generated worldwide [1,2]. Therefore, the recycling of construction waste has focused primarily on the reuse of recycled aggregate (RA) obtained from concrete and asphalt waste. The fact that the RA consists of original aggregate and adhered mortar (AM) is no longer new knowledge for researchers in this discipline. This AM contributes to lowering the density and increasing the water absorption of RA compared to natural aggregate (NA) [3]. Thus, the effect of AM is considered to be crucial to the reduction in mechanical strength and durability commonly observed in recycled aggregate concrete (RAC) [4–7]. This may be one of the reasons why the strength of RAC decreases more as the RA replacement ratio increases. When replacing NA with 100% of RA, Xiao et al., [8] mentioned that the elastic modulus of RAC reduced by 45%, Domingo et al., [9] reported that drying shrinkage and creep were 70% and 51% higher at 180 days, respectively. In the study of Etxeberria et al., [10], as the RA replacement ratio increased to 25%, 50%, and 100%, the elastic modulus of RAC declined by 4%, 12%, and 15%, respectively. Elhakam et al., [11] reported that an increase in the RA replacement ratio not only lowers the mechanical strength but also reduces the bond strength. On the contrary, some studies have shown improvements in mechanical and durability properties with the use of RA. This can be attributed to the quality of the RA. It was observed that concrete made from RA obtained from high-strength concrete has higher mechanical strength than concrete with RA obtained from low-strength concrete [12,13].

In order to improve the properties of RAC, several methods have been discussed and proposed to remove the AM; microwave method [14,15], chemico-thermal treatment [16], biotreatment [17], acid treatment [18,19]. However, apart from their efficiency, some methods entail the use of specific equipment, additional fuel and energy, which makes the practical application of these methods difficult [20]. Quattrone et al., [21] found that the fuel-fed thermo-mechanical process for RA production consumes up to 62 times more non-reusable energy compared to the traditional RA production process consisting of crushing and screening. Therefore, it is necessary to produce high-quality RA in large quantities while reducing the energy consumed as much as possible. Perhaps a better option is to improve the properties of concrete in a way that does not require significant time, money, and energy. This approach can be attempted at the design and mixing stages. Tam et al., [22] proposed a two-stage mixing approach (TSMA). Unlike the traditional mixing approach, TSMA first put the aggregate and half of water to be used to form a cement slurry layer that fills cracks and voids of RA, after that, the cement and the other half of the water are added to complete the mixing. The effectiveness of this method has been verified in several studies [23–26].

Fathifazl [27] noted that the application of conventional mix design methods to make RAC increases the proportion of mortar and decreases the proportion of aggregates compared to natural aggregate concrete (NAC). And the author proposed an equivalent mortar volume (EMV) mix design method that separates RA into the AM and original aggregates for mixture proportioning. Various studies using the EMV mix design method have reported increased strength of concrete and reduced raw material consumption. Thus, this paper aims to review the fresh properties (slump, density, and air content), mechanical properties (compressive, tensile and flexural strength, and elastic modulus), and durability performance (drying shrinkage, chloride penetration, frost resistance, and sorptivity) of RAC designed with the EMV method. It also provides insight into the environmental benefits.

2. Equivalent mortar volume method

2.1. Mix design

Concrete is a mixture of coarse aggregate, fine aggregate, cement and water (Fig. 1(a)). However, in the existing conventional mix design methods, when concrete is produced by replacing NA

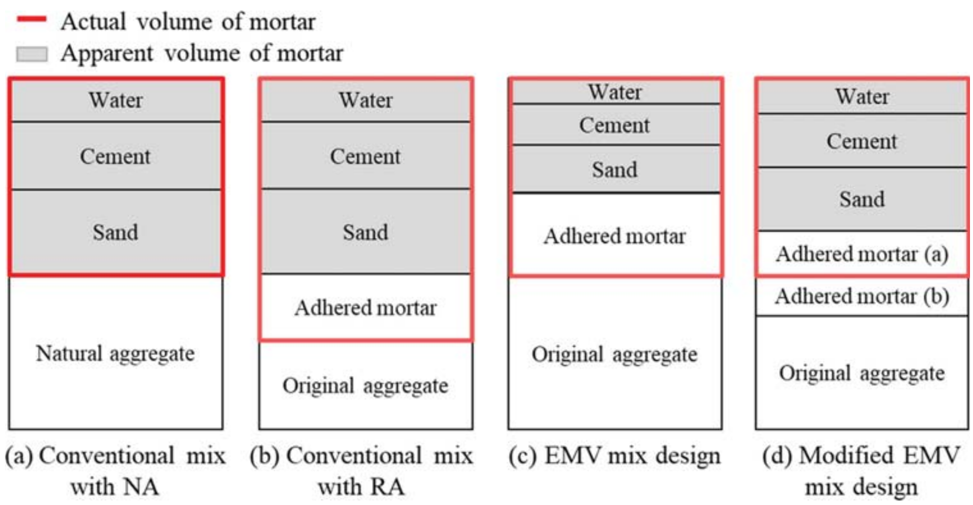

Fig. 1. Concrete mix designs (adapted from Yang and Lee [41]).

with RA partially or entirely, the total unit mortar in concrete rises, and the proportion of original coarse aggregate decreases due to the presence of the AM in the RA (Fig. 1(b)). Regarding the aggregate-to-cement ratio, Poon and Lam [28] observed the compressive strength of concrete increases as the aggregate-to-cement ratio decreases, but when this ratio exceeded a certain point, the compressive strength began to decrease [29,30]. To solve this problem, Fathifazl et al., [31] proposed the EMV mix design method. In this EMV method, the AM constituting RA is regarded as mortar, and the original aggregate is considered as aggregate. Therefore, the volumetric ratio of the aggregate in NAC and the volumetric ratio of total aggregate (sum of NA and original aggregate in RA) in the EMV concrete are equivalent, and the volume ratio of mortar in NAC is equivalent to the total mortar volume (mortar plus the adhered mortar) in the EMV concrete (Fig. 1(c)). In theory, it seems plausible, but there is a drawback that is often mentioned with this EMV mix design. It is related to the replacement ratio of RA. In the EMV method, the amount of newly added cement, sand and water is subtracted by the amount of the AM attached to RA, thus, when a large amount of NA is replaced with RA, the amount of fresh mortar is reduced, leading to poor workability of RAC in the fresh state. In particular, it is more challenging to replace NA with RA with a high adhered mortar content (AMC). To overcome these shortcomings, modified EMV methods have been proposed by various researchers (Fig. 1(d)) [32–35]. The modified EMV methods treat only a certain proportion of the AM in the RA as mortar, thus, the amount of new cement, sand, and water increases compared to the original EMV mix design to obtain proper workability.

2.2. Determination of adhered mortar content

In order to apply the EMV method, the AMC on RA should be estimated precedently. Several methods have been proposed for the determination of the AM, freeze-and-thaw with sodium sulfate solution method, thermal treatment, and acid treatment are often used (Fig. 2). One thing to note is that before the treatment, the foreign matter needs to be removed from the RA as much as possible. Even if RA is produced from concrete waste, the foreign matter can be contained during the material transport and storage. If RA with asphalt is contained, it will affect the accuracy of the measurements and contribute to inappropriate mixture proportioning [33].

The freeze–thaw method was proposed by Abbas et al., [36] who proposed the original EMV mix design. After sampling the representative RA by size, the sample is immersed in a 26% sodium sulfate solution for 24 h. Afterward, the samples go through freezing at −17 °C for 16 h and thawing at 80 °C for 8 h. A total of 5 cycles of freezing and thawing are repeated. Juan and Gutiérrez [37] proposed a thermal treatment method. The RA, which is soaked in water for 2 h to saturate the AM, is placed in a muffle at 500 °C for 2 h and then immersed in cold water. It causes cracks and stresses in the mortar, separating it from the original aggregate.

A method of removing mortar using acid solution was proposed by Tam et al., [18]. RA is soaked in 0.1 mol/l hydrochloric acid (HCl) and sodium sulfate solution for 24 h to dissolve and remove the AM. Ismail and Ramli [38] reported a linear correlation between the molar concentration of the hydrochloric acid solution and the mortar loss. Also, the authors concluded that the use of low-concentration acids does seem harmful to RA because the acid chloride remaining in the RA is within the standard range. This method has a shorter test duration than the freeze–thaw method and does not require human intervention after the RA is immersed in the solution. In addition, no additional equipment and energy are required as in the thermal treatment method. However, the acid treatment can overestimate the AMC for calcareous aggregates [39], while, for granite, this method can be one of the suitable options [40]. The remaining mortar after the treatments can be removed using a metal brush or a rubber mallet. After sieving to remove the aggregate of less than 4.75 mm fraction, the AMC is calculated by comparing the oven-dry weight before and after the test.

3. Properties of recycled aggregate concrete with EMV mix design

3.1. Fresh properties

3.1.1. Workability

Fathifazl et al., [31], who proposed the original EMV mix design method, reported that the EMV mix design method improved the slump of concrete. In the experiment, limestone and river gravel RA were used. The replacement ratio of RA of the conventional RAC was 100%, and that of EMV concrete was 60–70%. According to the test results, the slump of EMV concrete blended with Portland cement was 105 mm (limestone) and 140 mm (river gravel), respectively, which was more workable than that of conventional RAC of 70 mm. The workability of EMV concrete further improved in combination with supplementary cementitious materials. EMV concrete with 25% fly ash (FA) had a slump of 120 mm (limestone) and 140 mm (river gravel). While, with 35% blast furnace slag (BFS), EMV concrete made with limestone RA has a slump of 80 mm, which is about 24% decrease compared to Portland cement, but that of EMV concrete with river gravel RA has increased by 50% to 210 mm. However, the result that the EMV mix design method

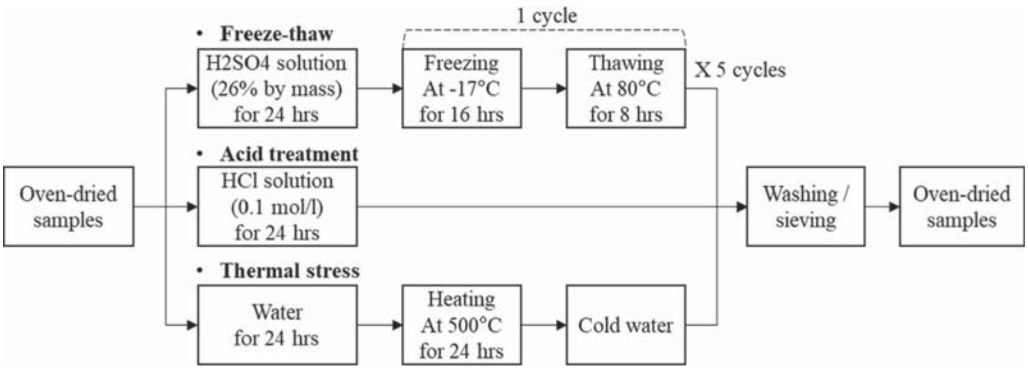

Fig. 2. Experimental scheme of different methods for determining adhered mortar content.

improved the slump of concrete is opposite to the experimental results reported by other researchers. Yang and Lee [41] reported that the slump of conventional RAC using 50% and 100% RA was 150 mm and 120 mm, respectively, which was higher than the slump of 80 mm of EMV concrete with 50% RA. In the study of Yang and Lee [34], at the RA replacement ratio of 50%, the slump of EMV concrete declined by 36% and 48%, compared to NAC and RAC with the conventional mix design.

The influence of the increased water-to-cement (w/c) ratio of EMV concrete was carried out by Jiménez et al., [42], as the w/c ratio increased from 0.45 to 0.60, the slump of two EMV concrete mixtures decreased from 100 mm to 90 mm and from 60 mm to 50 mm. In general, due to the high absorption capacity of RA, the slump value of RAC is lower than that of NAC [43–45]. In addition, as the proportion of the RA increases, the slump decreases, resulting in unworkable concrete in the fresh state. This lack of fluidity of concrete mixture is remarkable in the EMV mix design where cement, sand, and water are reduced by the amount of the AM. Hayles et al., [33] mixed RAC with 50% and 81% RA replacement by the EMV mix design without any admixtures. In the study, the slump was 190 mm for NAC, but the EMV concrete made of RA, which has AMC of 25.3%, decreased to 135 mm and 20 mm when using 25% and 100% RA, respectively. As expected, the slump loss of the EMV concrete with high AMC increased. For the EMV concrete with 41% of AMC, the slump values were 45 mm and 0 mm when using 25% and 100% RA. Kim et al., [46] mentioned that the complete replacement of NA with RA with 50% of the AMC did not provide adequate workability for specimen preparation. The low fluidity of concrete adversely affects its pumpability and may not be suitable for use in building structures. However, it can be favorably applied to road pavement and prefabricated concrete products with low slump requirements. The use of water-reducing agents and admixtures can improve workability to some extent. Yang and Lim [47] reported that the slump value of the EMV concrete could be comparable to that of NAC by increasing admixtures by 9%. To an extreme degree, Anike et al., [48] increased the amount of superplasticizer six times higher than that of NAC, and as a result, the slump of EMV concrete increased by 50% than that of NAC (Fig. 3). Overuse of admixtures may reach the same slump value, however, it may cause bleeding and segregation in a concrete mixture [49,50].

3.1.2. Density and air content

Due to the porous AM in RA, RA and RAC are generally less dense than NA and NAC [51,52]. However, the use of the EMV mix design can improve the density of RAC (Fig. 4). In the study [31], the density of conventional RAC was −1.5% lower than that of NAC, but the EMV concrete showed a similar density to NAC. In the study [42], the EMV concrete showed about 5.4–8.8% higher fresh density and 6.7–9.8% higher hardened density than RAC with the conventional mix design. Similar observations are shown in another study [48]. Moreover, the EMV concretes with FA and BFS were about 12% and 24% denser than the conventional RAC with Portland cement [31]. The higher density of the EMV concretes can be attributed to the difference in the RA replacement ratio from the control concretes. For the control concretes, 100% of RA replaced NA, whereas approximately 60–70% of RA was used for the EMV concretes. That is, 30–40% of the EMV concretes is composed of NA, which is basically denser than RA. Yang and Lim [47] measured the density of conventional RAC and EMV concrete with a fixed RA replacement level (i.e. 68%). As a result of the experiment, the density of conventional RAC and EMV concrete was 3.5% and 5.5% lower than that of NAC, respectively. Yang and Lim [47] also fabricated three RAC mixtures (i.e. RAC1, RAC2, RAC3) as per the modified EMV method. The original EMV mix design method was applied to RAC1. RAC2 considered only half of the AMC in RA as mortar, and only one-third was considered mortar for RAC3. Hence, the RAC2 mixture had a higher amount of new mortar than RAC1 mixture, and RAC3 had more than RAC2. As new mortar increased (i.e. as the total unit volume of the mortar in concrete increased), the density increased to 2187 kg/m^3, 2207 kg/m^3, and 2233 kg/m^3. Therefore, the authors mentioned that the density of EMV concrete can be improved by applying the modified EMV method, and studies to find the optimal mixture proportion should be conducted.

The density and air content of concrete have an inverse relationship [53]. As the RA proportion rises (i.e. as the total amount of the adhered mortar increases), the entrapped air in the concrete matrix increases, resulting in a decrease in density and an increase in air content [54–56]. Hayles et al., [33] made EMV concrete without chemical admixtures and assessed air content. The air content of the EMV concrete made by 100% of RA with the AMC of 25.3% was 2.9%, while the EMV concrete, with 81% of RA with the AMC of 41%, noticeably increased to 12.5%. The authors observed that the air content was measured to be high because the aggregate was not completely coated due to the lack of fresh mortar. In other studies [31,42], the application of the EMV mix design contributed to the reduction of air content. However, except in extreme cases where no chemical admixtures were used [33], the air content of the EMV concrete with a superplasticizer is not significantly different from that of the control group of NAC [34,41,57].

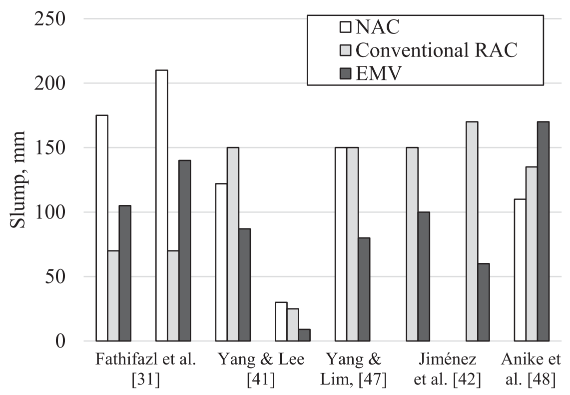

Fig. 3. Slump of concrete mixes designed by conventional and EMV mix design.

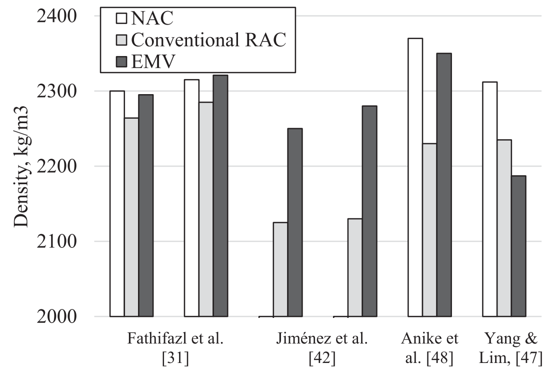

Fig. 4. Density of concrete mixes designed by conventional and EMV mix design.

3.1.3. Summary of influencing factors

The above-discussed parameters influencing the fresh properties of EMV concrete are summarized in Table 1. The EMV mix

Table 1
Influence of different parameters on the fresh properties of EMV concrete.

Parameter	Changes	Effect	References
RA content	↑	Negative	[34,41]
RA quality (AM content, high density, low absorption)	↓	Strong negative	[33,46]
w/c ratio	↑	Mild negative	[42]
Chemical admixture	↑	Strong positive	[33,47,48]
RA type / shape	–	Mild positive	[31]
RA pre-socking	–	unknown	–

design method appears to be unfavorable for the workability of concrete. In particular, using RA with a high AMC can be the worst. However, it appears that the density and air content of EMV concrete, including slump, can be controlled by chemical admixtures. In the context, pre-soaking, in which RA is soaked in water for a certain period of time before concrete mixing, may be considered as one of the ways to improve the workability of RAC [10,58]. Poon et al., [59] mentioned that the slump loss was significant when RAs in oven-dry and air-dry states were used. However, the EMV method-related studies referenced in this paper did not mention pre-soaking, thus, it was not confirmed whether it was implemented. Given the effect of pre-soaking, this needs to be discussed in further studies.

3.2. Hardened properties

3.2.1. Compressive strength

The compressive strengths of NAC, conventional RAC, and EMV concrete extracted from the various studies are shown in Fig. 5. In the 28-day compressive strength test conducted by Fathifazl et al., [31], the EMV concrete measured to be 39.2 MPa and 40.0 MPa, respectively, indicating a range of −7% to 1% of the conventional RAC. The authors concluded that using the EMV mix design method can achieve the same mechanical properties as NAC. To verify the effect of RA quality on mechanical properties of EMV concrete, Kim et al., [46] evaluated the compressive strength of EMV concretes using two RAs (RA1 and RA2) obtained from the same source but with different AMC of 12% and 50%, respectively. The water absorption of RA1 and RA2 was 2.87% and 6.07%, and the specific gravity was 2.50 and 2.26. It corresponds to the first (i.e. high-quality) and third class (i.e. low-quality) in KS F2527 [60], JIS A5021 [61], JIS A5023 [62], GB/T 25,177 [63] and RILEM TC121-DRG [64] standards based on water absorption. For conventional RAC, the compressive strength decreased as the RA quality

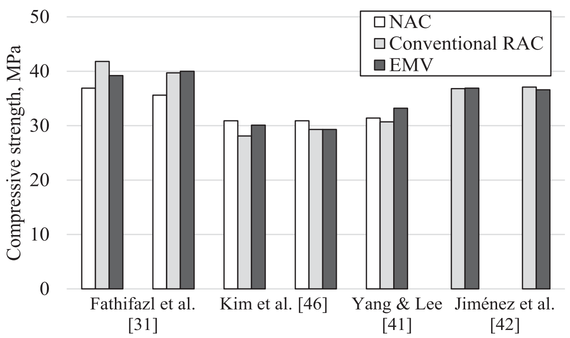

Fig. 5. Compressive strength of concrete mixes designed by conventional and EMV mix design.

decreased and the RA replacement ratio increased. At 25%, 50%, and 100% of RA replacement, the compressive strength of conventional RAC with high-quality RA was 30.9 MPa, 29.3 MPa, and 28.1 MPa, while the conventional RAC with low-quality RA was 27.9 MPa, 25.8 MPa, and 23.6 MPa. For EMV concrete, the compressive strength was in the range of 29.3 – 31.5 MPa regardless of the RA quality and replacement ratio. Therefore, the authors concluded that there is a strong correlation between the total volume amount of mortar in concrete and the compressive strength. Yang and Lee [41] attempted to verify the effectiveness of the EMV method by comparing the EMV concrete with the conventional RAC at the same RA replacement levels. At 50% RA replacement, EMV concrete had about 8% higher compressive strength than that of conventional RAC, but at 100% of replacement, the conventional RAC showed about 9% higher compressive strength. The effect of the water-cement ratio in EMV concrete was reported by Jimenez et al., [42], the compressive strength decreased by 30% when the water-cement ratio was increased from 0.45 to 0.60. In tests with the EMV and modified EMV concrete, contradictory test results were observed. In [65], the compressive strength of the original EMV was about 8.5–9.5% higher than that of the modified EMV concrete, whereas, in another study [47], the modified EMV concrete showed 7.8% higher compressive strength. Therefore, the authors noted that in-depth research should be conducted to find the optimal mix proportion.

The EMV mix design method has been applied to various types of concrete. Anike et al., [66] manufactured steel fiber reinforced RAC with the EMV mix design, and Rajhans et al., [67] produced self-compacting RAC using the EMV method. Fathifazl et al., [31] partially replaced Portland cement with supplementary cementitious materials in the EMV concrete. When 35% of Portland cement was replaced with BFS, the 28-day compressive strength of the EMV concrete decreased by about 12%, while with 25% of FA, the strength increased by about 6.5%. This trend was observed in conventional RAC with BFS and FA [68,69], but little data is available on the influence of supplementary cementitious materials on EMV concrete.

It is worth pointing out that the RA replacement ratios of the EMV concretes were lower than that of conventional RAC in most cases. This is because the increase of RA under the EMV mix design contributes to the poor workability of the concrete in the fresh state [70]. Nevertheless, if the EMV mix design method is applied with an appropriate RA replacement ratio, the compressive strength of concrete can be improved and the additional advantage of material saving can be achieved.

3.2.1.1. Tensile strength and flexural strength. Anike et al., [48] reported that EMV concrete with 40% of RA had 12% higher splitting tensile strength than NAC, and Sadati and Khayat [71] mentioned that the tensile and flexural strength of the EMV concrete with 30% of RA showed 8% and 17% higher than that of NAC. Yang [65] compared the tensile and flexural strength of the original EMV and the modified EMV mix design, which increased the amount of new mortar slightly more than the original EMV method. At the RA replacement ratios of 50% and 100%, the 28-day tensile and flexural strength of the EMV concrete was 4–11% and 4–10% higher than that of modified EMV concrete. The tensile strength can be reinforced with steel fibers. In the study conducted by Anike et al., [66], the tensile strength of the EMV concrete with 0.5% of steel-fiber was 10% higher than that of NAC, whereas the flexural strength has decreased by up to 17%. Regarding it, Matias et al., [72] concluded that RA adheres better to the cement paste than NA because of its rougher surface, which increases the tensile strength of RAC. González and Martínez [73] mentioned that the effect of the RA replacement ratios may be insignificant on the tensile strength of RAC, and it was noted that the strength seems to depend on the binder and RA quality rather than the type of aggregate [74,75]. In the flexural performance test, Yang and Lee [41] observed that the ultimate moments of the EMV RC beams with 40% and 80% of RA, respectively, were 1% and 5% higher than that of the conventional RAC beam with 40% of RA replacement. It was also mentioned that the crack propagation and failure modes of the EMV concrete beams with 40% RA replacement were similar to those of NAC. This trend was also observed in the studies [76–78]. According to the authors, no differences were observed in failure mode, crack pattern, and shear performance between the conventional RC beam and the EMV RC beam.

The relationship between compressive strength and splitting tensile strength is shown in Fig. 6 together with a splitting tensile strength prediction model provided by the ACI Committee 318 [79]. Although data collected from different literature, the correlation coefficient between compressive and splitting tensile strength is 0.89, demonstrating that the two strengths are positively correlated with the EMV mix design.

3.2.1.2. Modulus of elasticity. The elastic modulus of NAC, conventional RAC, and EMV concrete collected from the various studies are shown in Fig. 7. In the study of Fathifazl et al., [31], the elastic modulus of EMV concrete was 0–5% and 5–11% higher than that of NAC and conventional RAC. In the study [41], at 50% of the RA ratio, the elastic modulus of the conventional RAC was 23.5 GPa, whereas that of EMV concrete increased by about 6% to 25.1 GPa. Similar observations are found in the other study of the authors [47]. The authors noted that an increase in the total mortar volume could be a crucial factor leading to a decrease in the elastic modulus of conventional RAC. In other words, since the volumetric ratio of each material constituting the EMV concrete is equivalent to NAC, the final properties of concrete may have small differences. A study conducted by Kim et al., [46] showed that the AMC of RA itself does not seem to have a significant effect on the elastic modulus of concrete designed by the EMV method. For the EMV concrete with the high-quality RA with the AMC and water absorption of 12% and 2.87%, the 28-day elastic modulus with 25%, 50%, and 100% RA replacement ratios was 22.6 GPa, 22.9 GPa, 23.2 GPa. With the low-quality with AMC and water absorption of 50% and 6.07%, the elastic modulus of the EMV concretes was 22.2 GPa, 23.4 GPa at the same replacement level. It is worth mentioning that both RAs have the same original aggregate. On the contrary, the conventional RAC with the high-quality RA showed 22.7 GPa, 22.4 GPa, and 23.6 GPa, making no significant difference from the test results of the EMV concretes. However, for the RAC with the low-quality RA, the elastic modulus was 20.6 GPa, 19.3 GPa 17.4 GPa, which clearly shows that the elastic properties decrease with increasing RA replacement rate. However, even for the EMV concrete, if low-quality RA is used at a high replacement ratio, it may cause a decrease in the elastic modulus. Yang and Lee [34] measured the elastic modulus of EMV concrete at different RA replacement levels using high- (water absorption of 1.98%) and mid-quality (water absorption of 4.45%) RAs. At 25% and 50% replacement, the elastic modulus of EMV concrete mixed with mid-quality RA was 3% and 5% higher than that of NAC, respectively. However, at 75% incorporation, it decreased by 13% compared to NAC. The EMV concrete using high-quality RA had the same elastic modulus as NAC at 50% replacement, but increased by 3.7% at 100%.

Fathifazl et al., [31] reported that the elastic modulus of EMV concretes incorporating 35% of BFS and 25% of FA, respectively, was 5–15% higher than that of the conventional RAC. This is in contrast to the range of compressive strength for the same mixture being −18% to 1%. Since RAs have a lower modulus than NAs, in general, the elastic modulus of RAC is affected by the replacement ratio of RA [80], and it has been reported that the elastic modulus decreases even when the strength increases [8,10], however, no such trend was observed in the EMV mix design method.

Fig. 8 shows the correlation between compressive strength and elastic modulus of concrete mixes designed by the EMV, modified-EMV and conventional mix design collected from the literature.

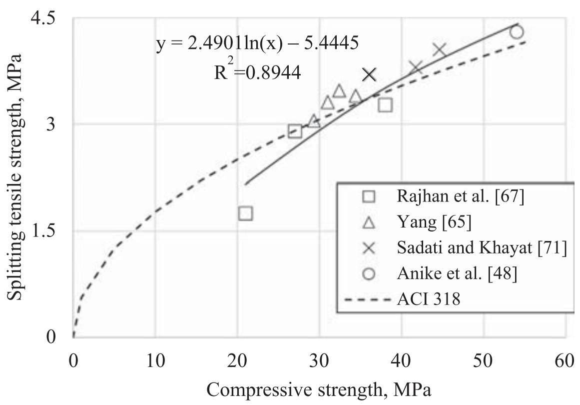

Fig. 6. Relationship between compressive and splitting tensile strength of EMV concrete mixes.

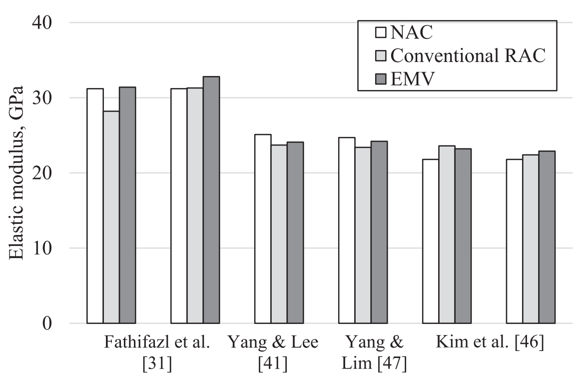

Fig. 7. Elastic modulus of concrete mixes designed by conventional and EMV mix design.

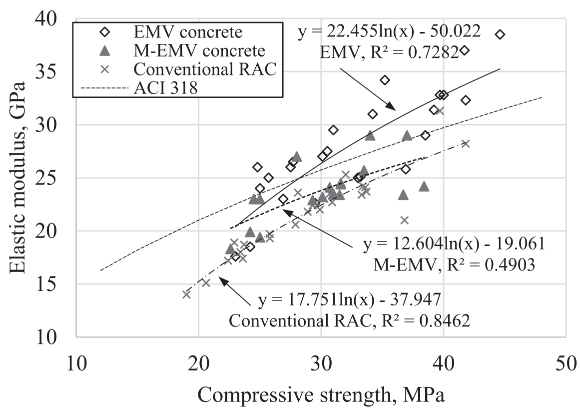

Fig. 8. Relationship between elastic modulus and compressive strength of EMV concrete mixes.

The correlation coefficients for each group are 0.73, 0.49 and 0.85. The low correlation coefficient of modified EMV concrete can be attributed to the fact that the effective volume fraction of AM is determined based on the empirical knowledge of each researcher. For example, at 50% RA replacement level, one researcher might consider only half of the AM in RA to be mortar, while another might assume that only one-third of the AM is effective. Also, even in studies using the same aggregate, the effective fraction of adhered mortar varies depending on the level of replacement. Therefore, the inconsistent proportions of aggregate and mortar in the modified EMV concrete may be responsible for the low correlation coefficient. As shown in Fig. 8, at the same strength level, the elastic modulus of modified EMV concretes appears to be similar to or slightly higher than that of conventional RAC while EMV concrete clearly shows a higher elastic behavior compared to that of modified EMV and conventional RAC.

3.2.1.3. Summary of influencing factors. Table 2 shows the parameters affecting the mechanical properties of EMV concrete. Compared to conventional RAC, it seems clear that the EMV and modified EMV mix designs improve mechanical strength. However, extensive data are needed to deeply analyze the effect of the EMV mix design on the mechanical properties of concrete. In particular, the history of RA needs to be included. This is because RA produced from high-strength parent concrete has a positive effect on the mechanical properties of next-generation concrete [12,13,81].

3.3. Durability performance

3.3.1. Drying shrinkage

Drying shrinkage of RAC is affected by the porosity, elastic modulus, and the amount of AM, etc. The high porosity results in high water absorption, which is disadvantageous for mitigating the drying shrinkage [82]. Therefore, in EMV concretes, which have a lower total amount of mortar compared to the conventional mix design, it can be expected to restrain drying shrinkage deformations. According to a study by Fathifazl et al., [83], the drying shrinkage strain of two different EMV concretes was higher than that of conventional RAC at early ages. However, as of the 45th and 75th days of age respectively, the strain of the conventional RAC exceeded that of the EMV concretes. In the study [41], the drying shrinkage deformations of the conventional RAC were 1204 μm/m at 41 days, which was 42% higher than that of NAC. While the deformations of the EMV concretes with 40% and 80% RA replacement increased by 17% (996 μm/m) and 22% (1039 μm/m), respectively. That is, the shrinkage deformation of the EMV concretes were higher than that of NAC, but lower than that of RAC with the conventional mix design. Also, an increase in the RA replacement ratio appears to contribute to the increased drying shrinkage of EMV concrete. This is clearly observed in the study [57]. Yang and Lee [57] assessed the drying shrinkage of EMV concrete mixtures with different replacement ratios of RA (22.8%, 46.8%, and 72.6%). At 105 days, the drying shrinkage deformation of each concrete was 530 μm/m, 660 μm/m, and 700 μm/m, which were 26.6%, 8.6%, and 3% lower than the NAC of 722 μm/m. For comparison, the deformation of the conventional RAC with 47% RA replacement was 816 μm/m, which was 13% higher than that of NAC (Fig. 9). Therefore, the authors concluded that the unit volume of mortar in concrete and the drying shrinkage deformation is proportional. When replacing NA with RA, the decreased shrinkage deformations of the EMV concrete can also be found in other studies [47,65,71].

Table 2
Influence of different parameters on the mechanical properties of EMV concrete.

Parameter	Changes	Effect	References
RA content	↑	Insignificant or mild negative	[31,41,46]
RA quality (AM content, high density, low absorption)	↓	Mild negative	[46,47]
w/c ratio	↑	Negative	[42]
Properties of parent concrete		unknown	–

3.3.2. Frost resistance

The frost resistance of RAC is affected by the RA replacement ratio like other durability performance [84,85]. Guo et al., [86] stated that the frost resistance of RAC may be degraded because water absorbed into the concrete can be drained into the cement paste of RA during freezing-and-thawing cycles. Fig. 10. presents the test result of relative dynamic modulus of concrete mixes performed by Yang and Lee [57]. After 300 cycles of freezing-thawing action, the relative dynamic modulus of NAC was 95.3%, and that of the conventional RAC with 47% RA replacement was 88.5%. While, the freeze–thaw resistance of the EMV concretes was lower than that of NAC and higher than that of RAC. At the RA replacement ratios of 22.8%, 46.8%, and 72.6%, the relative dynamic modulus of the EMV concretes were 95%, 93.6%, and 82.2%, respectively. Although the EMV concrete with RA replacement level of 73% showed a lower value than conventional RAC, it seems that the application of the EMV method can improve the freeze–thaw resistance of concrete incorporating RA. Similar research findings can

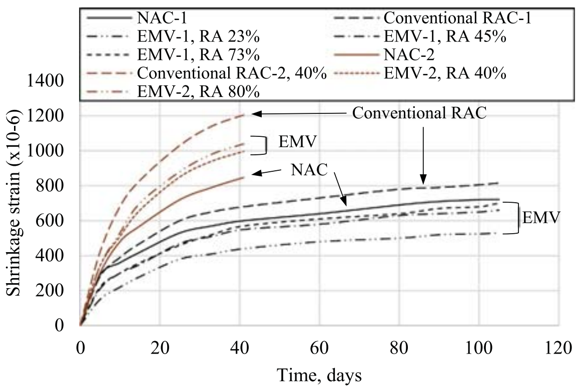

Fig. 9. Drying shrinkage deformation of concrete mixes [41,57].

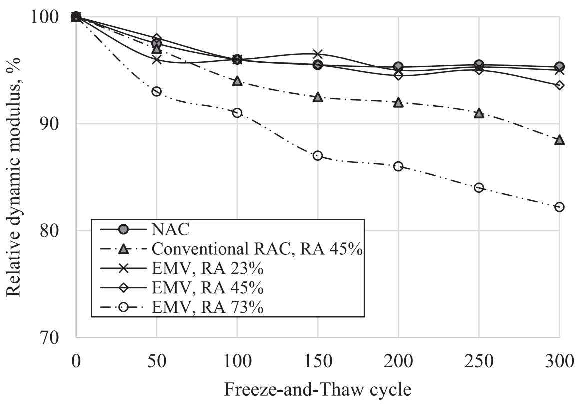

Fig. 10. Relative dynamic modulus of concrete mixes [57].

be observed in [71]. In the test on the durability of EMV concrete with supplementary cementitious materials performed by Abbas et al., [87], the results were contradictory. The EMV concrete with RA1 showed a higher freeze–thaw durability factor than the conventional mix method, while, with FA and BFS, the durability factors of the EMV concrete decreased. For the concrete with RA2, the durability factors showed higher under the conventional mix method. However, when BFS and FA were added, the factors of the EMV concrete were improved. The authors noted that even though the durability factors of some EMV concrete mixtures found to be lower than that of the conventional RAC, all the durability factors exceeded 90%, showing proper frost resistance.

3.3.3. Chloride penetration

Chloride penetration is one of the causes of concrete deterioration [88]. The presence of chloride ions in the concrete matrix affects the spalling of the concrete structure and accelerates rebar corrosion [89]. Jiménez et al., [90] found that the chloride diffusion of EMV concrete with a w/c ratio of 0.45 was about 19–48% higher than that of conventional RAC. In addition, it was observed that the chloride diffusion tends to be greater as the w/c ratio increases from 0.45 to 0.6. This observation is consistent with the findings in [87]. Abbas et al., [87] reported that the apparent chloride diffusion coefficient of the EMV concrete was about 9–10% higher than that of the conventional RAC. This can be attributed to the fact that the unit cement content of EMV concrete is smaller than that of conventional RAC. When the water-cement ratio is the same, a decrease in the unit cement content may weaken the resistance against chloride penetration [91]. The chloride penetration resistance of EMV concrete can be enhanced by the incorporation of supplementary cementitious materials. The use of FA as a partial replacement for cement reduced the diffusion coefficient of the EMV concrete by 39–54%, and with BFS, it reduced by 56–63% [87].

On the contrary, conflicting results were observed in studies measuring the resistance to chloride penetration by the flow of electric charge in accordance with ASTM C1202 [92]. Rajhans et al., [67] conducted a rapid chloride penetration test to measure the total charge passing through a concrete sample. In the study, the flow of electric current through the conventional RAC was about 60% higher than that of NAC, while the EMV concrete showed only about 10% higher electric current. The electric current passing through concrete indicates the movement of ions in the pore solution. Therefore, the high electric current flow means less durable concrete [93]. Similarly, in the study by Yang and Lee [94], the total charge passed through the EMV mix design method was reduced by 30–40% compared to that of the conventional RAC. The authors of both studies noted that the improved resistance to chloride penetration of EMV concrete was due to the reduced total mortar content than the conventional RAC. It may also be because the EMV concrete has less cracks and pores compared to conventional RAC [67,95,96]. However, given the experimental results mentioned in this section, it is not clear whether the EMV mix design has a positive or negative effect on chloride penetration resistance.

3.3.4. Water absorption

Moisture absorption of concrete is related to resistance to chemical attacks, such as sulfate ions, chloride ions, and alkali ions [97]. Generally, the RA replacement ratio and water absorption in concrete are proportional, which is due to the pores or micro-cracks of the RA that occurred during the RA production [98,99]. Anike et al., [48] evaluated the water absorption capacity of NAC, conventional RAC, and EMV concrete. At 28 days, the water absorption of the three concretes was measured to be 3.1%, 5.6%, and 3.4%, respectively, in the order of NAC, EMV concrete, and the conventional RAC. The same results have also been observed in [66]. Jiménez et al., [90] reported that the capillary absorption coefficient of the conventional RAC mix was about 1.7–4.2 times higher than that of EMV concrete. In a water penetration test conducted for 72 h with a water pressure of 500 kPa, the conventional RAC allowed 1.21–1.87 times higher penetration compared to the EMV concrete. The authors noted that the enhanced resistance to water absorption of the EMV concrete is theoretically due to the smaller capillary pores in the EMV concrete than in the conventional RAC.

4. Environmental impact

Table 3 shows the quality requirements for RA for concrete specified in various standards, specific gravity and water absorption of RAs used in the studies referenced in this review paper. Regarding the quality of RA, KS F2527 [60] and RILEM TC121-DRG [64] stipulate that the requirements of RA for concrete to have a minimum oven-dried density of 2.5g/cm^3 and 2.4 g/cm^3, respectively, and the maximum water absorption is 3%. JIS [61,62,100] and GB/T 25,177 [63] classify RA into three grades: high (H), medium (M), and low (L) quality. For high quality RA, the minimum densities in both regulations are 2.5g/cm^3 and 2.45g/cm^3, respectively, and the maximum absorption is 3%. For medium quality, the densities are 2.3g/cm^3 and 2.35g/cm^3, and the water absorption is 5%. For low quality RA, JIS has no requirement for density, and the required maximum water absorption is 7%. GB/T 25177, on the other hand, has a density and absorption of 2.25 g/cm^3

Table 3
Physical properties of RA used for EMV concrete.

Reference	Class	Specific gravity	Water absorption, %	RA replacement, %
KS F2527 [60], JIS A:5021 [61]	H	2.5	3	–
JIS A:5022 [100] / GB/T 25,177 [63]	M	2.3 / 2.35	5	–
JIS A:5023 [62] / GB/T 25,177 [63]	L	None / 2.25	7 / 8	–
[31]	L / M	2.42/2.5 (SSD)	5.4/3.3	63.5/74.3
[33]	M / M	2.36/2.39 (bulk)	3.43/3.13	50/81/100
[34]	L / L / M / H	2.37/2.42/2.35/2.54 (-)	5.39/5.37/4.45/1.98	25–100
[35]	M	2.28 (-)	4.33	25–100
[41]	M	2.49 (-)	4.51	50/100
[42]	M / L	2.31/2.33 (OD)	4.7/6	65/68
[46]	L / H	2.4/2.56 (SSD)	6.07/2.87	25/50/100
[48]	L	2.30 (OD)	5.25	40
[57]	M	2.35 (-)	4.45	23/45/73
[65]	L / M	2.34/2.52 (-)	6.61/3.82	50/100
[67]	H	2.54 (bulk)	2.33	63
[71]	M	2.38 (-)	4.2	30

*-: not found in the literature; SSD: saturated-surface-dry; OD: oven-dry.

Table 4
Quantity of raw materials and material savings.

References	RA		Method	Material savings, %			Mechanical properties			
	Class	Replacement, %		Water	Cement	Sand	CS, MPa		Ec, GPa	
[31]	L	100	C	–	–	–	41.8	–	28.2	–
	L	63.5	E	−3.2	−4	−29.1	39.2	−6.2%	31.4	+11..3%
	L	100	C	–	–	–	34	–	28.1	–
	L	63.5	E	−3.8	−4.2	−29.1	34.2	+0.6%	31	+10.3%
	L	100	C	–	–	–	42	–	–	–
	L	63.5	E	−3.8	−4	−29.1	41.8	−0.5%	32.3	–
[42]	L	100	C	–	–	–	36.8	–	–	–
	L	65	E	−23.9	−24	−23.3	36.9	+0.3%	–	–
	L	100	C	–	–	–	26.4	–	–	–
	L	65	E	−23.9	−24.1	−23.2	26.9	+1.9%	–	–
[41]	M	50	C	–	–	–	30.7	–	23.5	–
	M	50	E	−11.7	−11.7	−13.6	33.2	+8.1%	25.1	+6.8%
	M	100	C	–	–	–	33.7	–	23.7	–
	M	100	E	−13.9	−14.4	−16.6	30.7	−8.7%	24.1	+1.7%
[47]	M	68	C	–	–	–	33.3	–	23.4	–
	M	68	E	−22.5	−22.3	−22.3	34.3	+3%	24.2	+3.4%
	M	68	E	−8	−10.8	−11	38.4	+15.3%	24.2	+3.4%
[46]	H	25	C	–	–	–	30.9	–	22.7	–
	H	25	E	−2.9	−2.8	−2.7	29.5	−4.5%	22.6	−0.4%
	H	50	C	–	–	–	29.3	–	22.4	–
	H	50	E	−2.9	−3.1	−3.2	29.3	0%	22.9	+2.2%
	H	100	C	–	–	–	28.1	–	23.6	–
	H	100	E	−5.7	−5.8	−5.9	30.1	+7.1%	23.2	−1.7%
[71]	M	0	C	–	–	–	43.5	–	35.5	–
	M	30	E	−12.4	−12.7	−7	41.7	−4.3%	37	+4.2%

* C: conventional mix design; E: EMV mix design CS: compressive strength; Ec: elastic modulus.

and 8%. As shown in Table 3, the specific gravity of RAs used in EMV concrete production is 2.28–2.56, and the water absorption is 2–6.6%, indicating that medium and low quality RAs were mainly used. This is similar to the physical properties of RAs produced using ordinary laboratory crushers without advanced processing [101,102]. This means that even if the RA is not of high quality, it can be sufficiently used for concrete purposes under the EMV mix design method, thereby reducing the number of recycling facilities for the production of high quality RA and energy consumption. This can enable the reuse of construction waste at reconstruction sites with minimal recycling facilities. Compared to stationary recycling plants, the benefits of on-site recycling include reduced transportation costs, reduced dust and noise pollution, and ease of waste management [103]. In particular, transportation of construction waste and RA is one of the factors that have the greatest impact on the economy and environment [104]. Jung et al., [105] stated that on-site recycling reduces cost and carbon dioxide emissions by 63.8% and 33.6%, respectively, compared to plant recycling. Therefore, if the RA is produced and used on-site, it can increase the value-added and economical efficiency of the RA, particularly in large-scale demolition projects [106].

Table 4 shows the RA class, replacement ratios used for conventional RAC and EMV concrete and the material savings by weight. To check the effectiveness of the EMV mix design method, the compressive strength and elastic modulus are included in the table. In the study of Fathifazl et al., [31], the use of sand was reduced by 29.1% compared to the conventional mix design. In the study of Jiménez et al., [42], the quantity of raw materials declined by 23–24%, and the compressive strength increased by 0.3–1.9%. Yang and Lee [41] saved the materials by about 11.7–13.6%, and the compressive strength and elastic modulus rose by 8.1% and 6.8%, respectively. Sadati and Khayat [71] reduced water and cement by about 12%, resulting in a 4% decrease in compressive strength and a 4% increase in elastic modulus. A reduction in raw material consumption and an increase in mechanical strength were also reported in [46,47].

According to Zhang and Wang [107], from 2005 to 2012 in China, steel and cement accounted for 87% of the total CO_2 emissions from the building material manufacturing stage. Also, the transport of these two materials contributes approximately 90% of CO_2 emissions at the material transport stage. Therefore, even if the EMV concrete has lower mechanical strength than conventional concrete, if it can satisfy the target properties, the EMV method can be economical and environmentally friendly option since it reduces the use of raw materials. According to the life cycle assessment performed by Jiménez et al., [108], the two things that have the greatest impact on the environment are cement and NA. Moreover, the authors noted that the EMV method leads to the overuse of chemical admixtures to improve workability, but this does not undermine the environmental benefits of the EMV mix design.

5. Conclusions

This paper reviewed the physical, mechanical, durability properties, and environmental benefits of RAC designed with the EMV mix design. It can be concluded that the application of the EMV mix design appears to make a promising contribution to sustainable development in the construction industry by improving the mechanical and durability properties of RAC and reducing the use of raw materials than conventional mix design. Though the EMV concrete mixtures showed low slump values in most cases, it seems that the use of chemical admixtures can achieve the minimum workability needed for concrete work. Furthermore, the EMV mix design enhances the properties of concrete in an eco-friendly way. Compared to conventional RAC, it consumes less amount of raw material, and high quality RA and additional treatment are not required. The EMV method is observed to be effective for medium quality RA with a water absorption rate of 3–5% and low-quality RA with absorption exceeding 5%. The application of the EMV mix design method has been expanded from plain concrete to reinforced concrete beams, steel fiber concrete, and self-compacting concrete. However, research data on other than the compressive strength, modulus of elasticity, and drying shrinkage of the plain EMV concrete are insufficient. Therefore, further studies need to be conducted to ensure the effectiveness of the method and the reliability of the results. Some of the future studies are as follows:

- Optimal mix proportioning for the EMV mix design needs to be formulated.
- Research on the long-term mechanical and durability behavior of EMV concrete are needed.
- The effects of pre-wetting, shape, rock type, and properties of parent concrete of RA on EMV concrete have not been investigated.
- A method to accurately measure the adhered mortar content of RA has to be established.
- Research data on the EMV method applied to concrete except for normal strength concrete. Studies on various types of concrete such as high strength concrete and self-compacting concrete should be conducted.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Influence of Mix Design on Physical, Mechanical and Durability Properties of Multi-Recycled Aggregate Concrete

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Abstract: The decrease in the quality of recycled aggregate due to an increase in the number of recycling is a primary factor that limits the multi-recycling of concrete. This degradation adversely affects concrete performance; thus, the characteristics of recycled aggregate should be considered during the mix design stage, but little research has taken that into account. This study investigates the effect of the equivalent mortar volume (EMV) mix design on some physical, mechanical and durability properties of concrete made of multiple recycled coarse aggregates at 50% and 100% replacement ratios compared to concrete made by the conventional mix design (CMD). The results showed that the performances of concrete by the CMD decreased with an increasing number of recycling cycles. The properties of EMV-based concrete deteriorated with an increase in the number of recycling cycles at 100% replacement ratio due to poor workability caused by a shortage of fresh mortar. However, at 50% replacement, the EMV-based concrete exhibited similar performance across the three cycles of recycling, as well as improved properties over natural aggregate concrete. This study demonstrated that an appropriate mix design and optimal aggregate replacement ratio can offset the property loss of multiple recycled aggregate concrete.

Keywords: true sustainability; repeated recycling; construction and demolition waste; concrete mix design; recycled concrete aggregate; green construction

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1. Introduction

Extensive and diverse studies on recycled aggregate for green construction have led to the establishment of various technical guidelines and standards for its use in many countries and institutes [1–6]. In general, recycled aggregate, particularly of coarse size obtained from concrete waste, is produced by crushing concrete made with natural aggregate in various ways. Concrete containing the recycled aggregate as raw material is named recycled aggregate concrete (RAC). Technically, this recycled aggregate is 'recycled aggregate used once'. However, in order to achieve sustainability in a true sense, a discussion of multiple recycling of recycled aggregate and RAC needs to be conducted.

To date, studies on multiple recycled aggregate concrete (MRAC) have been conducted by a limited number of scholars, but this topic is intriguing to many researchers, and the interest is clearly growing. In general, the multiple recycling of concrete progressively reduces its mechanical properties in proportion to the number of recycling cycles. In a study by Abreu et al. [7], the 28-day compressive strength of first, second, and third generation RAC decreased by 3.2%, 4.7%, and 13.1%, respectively, and the tensile strength decreased by 9.1%, 11.4%, and 15.1%, compared to natural aggregate concrete (NAC). Huda and Alam [8] also reported that the 28-day compressive strength and tensile strength of third generation RAC decreased by about 40% and 33% of those of NAC. Moreover, the third generation RAC required 120-day curing to achieve compressive strength similar to that of NAC. The multiple recycling also has unfavorable influences on the durability of concrete, such as frost, chloride and carbonation resistance [9]. In a study by Zhu et al. [10], third generation RAC was able to withstand only 600 cycles of freeze-thaw action unlike NAC and first and second generation RACs, which showed a relative dynamic modulus of approximately 55–65% after 800 freeze–thaw cycles. In addition, the chloride ion permeability coefficients of first, second and third generation RACs were 39.6%, 59.8%, and 84.9% higher than that of NAC.

The aforementioned studies have investigated the effect of multiple recycling of concrete and reported the progressive decrease in performance as the number of times of recycling increases [11–13]. As a rule, the quality degradation of recycled aggregate occurring in the repeated recycling is identified as the cause of the gradual decrease in MRAC performance [14]. It is a well-known fact that the quality of recycled aggregate is one of the parameters that govern the performance of RAC. The adhered mortar of recycled aggregate increases the total mortar volume of RAC and weakens the interfacial transition zone (ITZ) between aggregate and cement matrix, which is responsible for reducing performance. Thomas et al. [15] reported that third generation RAC has almost twice as much mortar content as first generation RAC, which limits the repeated recycling of concrete. In this context, it appears that there are certain limitations associated with the repeated recycling of concrete. However, no efforts have been made to address the performance degradation that occurs as a result of its multiple recycling. Hence, there is a need to conduct investigations aimed at finding solutions that can enhance the performance of MRAC, and the solutions should be as energy-friendly as possible, taking into account global trends towards the environment. At this point, the application of the equivalent mortar volume (EMV) method can be considered to offset the performance losses of the RAC caused by the degraded quality of the recycled aggregate. The EMV method is a type of mix design that maintains the volume of total mortar in RAC (i.e., the adhered mortar in recycled aggregate and fresh mortar) constant by considering the adhered mortar in recycled aggregate as mortar, not aggregate. Not only the mechanical and durability performance of the EMV-based concrete has been proven in many previous studies, but the EMV method is also considered to be eco-friendly and economical as it can save the amount of fresh mortar as much as the volume of adhered mortar of recycled aggregate [16–20]. In particular, the EMV method has been reported to be effective even for low-quality aggregates [21], which can be expected to contribute to enhancing the performance of MRAC by reducing the negative influence of the quality degradation of recycled aggregate caused by multiple recycling.

Therefore, this study aims to enhance the performance of MRAC. A series of MRACs containing once-, twice- and thrice-recycled coarse aggregates (RCA) were prepared by the conventional mix design (CMD) and the EMV methods, respectively, and their physical, mechanical and durability properties were analyzed. The obtained experimental data are expected to make an important contribution to complementing the lack of knowledge about MRAC. After all, the ultimate goal of this study is to explore true sustainability of concrete through multiple recycling.

2. Experimental Program

2.1. Research Flow

The experimental procedure of this study is shown in Figure 1. The experiment involved a series of concrete making and crushing processes to prepare first, second and third generation RCAs and RACs, which is then subjected to tests to evaluate their physical, mechanical and durability properties. The RCAs and RACs during three recycling cycles were defined as follows:

- RCA1: it refers to the first generation RCA produced by multiple crushing precast concrete members made of natural aggregate in a recycling plant.
- RAC1: the first generation RAC containing RCA1 is denoted as RAC1, and it is subdivided into R1-C-100, R1-E-50, and R1-E-100 according to the mix design and replacement ratio of RCA1.
- RCA2: the second generation RCA, RCA2, was obtained by crushing RAC1 with 100% RCA1 (i.e., R1-C-100 and R1-E-100) with a laboratory jaw crusher after 35 days of curing. In particular, R1-E-50, which contains 50% of natural coarse aggregate (NCA), was excluded from RCA2 production in order to ensure the representativeness of being recycled twice.
- RAC2: the second generation concrete uses RCA2, and it is divided into R2-C-100, R2-E-50, and R2-E-100 based on the mix design and RCA2 replacement ratio.
- RCA3: this refers to RCA obtained from RAC2 with 100% RCA2 (i.e., R2-C-100 and R2-E-100). For the same reason as in the RCA2 preparation described above, R2-E-50 was excluded from RCA3 production.
- RAC3: the third generation RAC. RAC3 was produced using RCA3 as a coarse aggregate, and it is classified into R3-C-100, R3-E-50, and R3-E-100 depending on the mix design and aggregate replacement ratio.

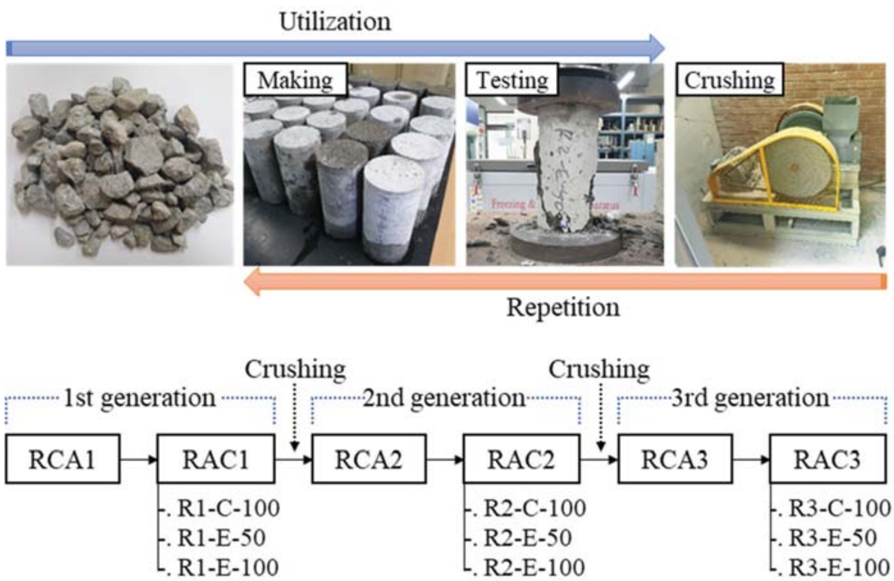

Figure 1. Experimental flow of multiple recycled aggregate concrete.

2.2. Materials

In this experimental research program, ordinary Portland cement was used as a binder, and its properties are provided in Table 1. For the fine aggregate, crushed sand with a nominal maximum size of 4.75 mm was used, and the water absorption and specific gravity were 1.09% and 2.59, respectively. For coarse aggregate, granite natural aggregate and three different generations of RCA (RCA1, RCA2, RCA3) were used (Figure 2), and the size fraction of 4.75–19 mm was selected through sieving. The particle size distribution and physical characteristics of the aggregates used are given in Figure 3 and Table 2.

Table 1. Properties of ordinary Portland cement.

Specific Gravity	Blaine Fineness, cm^2/g	Setting Time, min		Compressive Strength, MPa			Loss of Ignition, %
		Initial	Final	3-Day	7-Day	28-Day	
3.15	3720	220	305	32.0	42.4	51.8	2.2

Figure 2. Recycled concrete aggregates with different recycling generations.

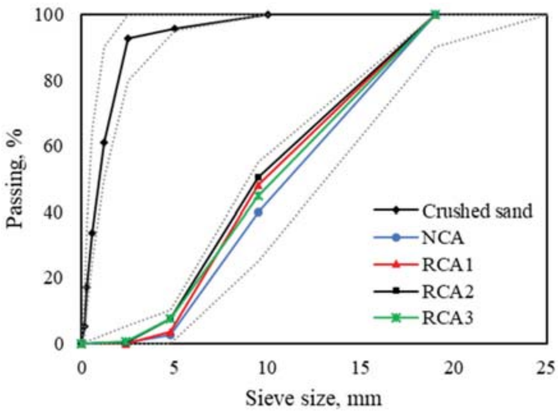

Figure 3. Particle size distributions of aggregates.

Table 2. Physical characteristics of aggregates.

Aggregate	Specific Gravity	Water Absorption, %	Adhered Mortar Content, %
NCA	2.696	0.73	-
RCA1	2.587	2.80	11
RCA2	2.400	6.92	23
RCA3	2.282	6.94	32

2.3. Mixture Design

In order to investigate the mechanical and durability properties of MRAC, a total of 10 concrete mixtures were designed by the CMD and the EMV design [22]: reference concrete, 3 series of RAC1, 3 series of RAC2, 3 series of RAC3.

The mix proportion of each mixture is detailed in Table 3. The CMD does not consider the variation of RCA characteristics caused by multiple recycling. Therefore, the CMD-based concretes (R1-C, R2-C and R3-C in Table 3) were designed with a constant amount of cement, sand and water required to make unit concrete. In contrast, with the EMV method, the mix proportion of concrete varied depending on the adhered mortar content in RCA. The volume of fresh mortar in EMV-based concrete was deducted by the volume of hardened mortar adhered to RCA, so that the EMV-based concrete had a constant aggregate–mortar ratio regardless of the amount of adhered mortar. As the adhesive mortar content of RCA increased with the number of recycling cycles, the amount of cement, sand, and water required for unit concrete decreased in the order of R1, R2, and R3. A detailed description of the mix proportions of concrete designed with the EMV method can be found in our previous studies [23,24].

Table 3. Mixture proportions (kg/m^3).

No.	ID	*w/c*	Cement	Sand	Water	NCA	RCA1	RCA2	RCA3	Plasticizer
1	NAC	0.4	410	811	164	948	0	0	0	3.28
2	R1-C		410	811	164	0	989	0	0	3.28
3	R1-E-50		388	767	155	474	532	0	0	3.10
4	R1-E-100		366	724	146	0	1065	0	0	2.93
5	R2-C		410	811	164	0	0	844	0	3.28
6	R2-E-50		348	689	139	474	0	615	0	2.78
7	R2-E-100		335	662	134	0	0	1013	0	2.68
8	R3-C		410	811	164	0	0	0	802	3.28
9	R3-E-50		315	623	126	474	0	0	697	2.52
10	R3-E-100		299	591	120	0	0	0	1128	2.39

- Reference concrete was prepared using natural aggregates, and the mix proportion provided by a ready-mixed concrete plant was adopted, which was set to achieve a 28-day compressive strength of 30 MPa and a slump of 180 mm.
- For RAC1, two mix designs were used: CMD and EMV. Concrete made by CMD was named R1-C, and the concrete made with the EMV mix design was divided into R1-E-50 and R1-E-100 based on the RCA1 replacement ratio.
- The RAC2 with the CMD was named R2-C, and RAC2 proportioned by the EMV design was divided into R2-E-50 and R2-E-100 depending on the RCA2 replacement ratio. Particularly, at 100% replacement ratio, the combination of RCA2 with adhered mortar content of 23% and the EMV design significantly reduced the amount of fresh mortar, making it nearly impossible to mold with the general compaction (not only zero slump, but hard to compact by steel rod), thus the modified EMV design proposed by Yang and Lee [25] was applied. The modified EMV method considers only a certain portion of the adhered mortar content of RCA as mortar and the remaining portion as aggregate, thereby increasing the amount of fresh mortar. In practice, the determination of the portion of mortar and aggregate in adhered mortar depends on the experience and knowledge of concrete designer. In this study, the mix proportion for R2-E-100 was designed by determining the adhered mortar content to be 12% instead of 23%.
- The RAC3 was classified into R3-C, R3-E-50 and R3-E-100 according to the mix designs and RCA3 replacement ratios. As in the case of RAC2, the modified EMV design was applied for R3-E-100. The adhered mortar content was considered to be 16% instead of 32%.

For all mixtures, the water-to-cement ratio was kept constant at 0.4, and the dosage of a polycarboxyl-based plasticizer was maintained at 0.8% of the cement mass as recommended by the manufacturer. The concrete mixing and specimen preparation were carried out in accordance with ASTM C192.

2.4. Test Methods

Workability, several physical, mechanical and durability properties of hardened concretes have been carried out. Some tests and devices used are presented in Figure 4.

The workability, a key performance indicator of fresh concrete, was determined by the slump cone test in accordance with ASTM C143.

The density and water absorption were measured to investigate the degree of porosity of concrete. The density was determined by dividing the mass in the saturated surface dry (SSD) state by the volume of the specimen. The water absorption was determined by subtracting the SSD mass by the oven-dry (OD) mass and dividing it by the OD mass.

Figure 4. Various tests on multiple recycled aggregate concrete: (**a**) compressive strength; (**b**) splitting tensile strength; (**c**) flexural strength; (**d**) drying shrinkage; and (**e**) rapid chloride penetration test.

The mechanical strength of the hardened concrete was measured using a hydraulic universal testing machine with a capacity of 1000 kN on specimens cured for 28 days. Compressive strength and splitting tensile strength were performed on cylindrical specimens with a size of 100 × 200 mm in accordance with ASTM C39 and ASTM C496, respectively. A load corresponding to a stress of 0.25 MPa/s for compressive strength and 1.0 MPa/min for splitting tensile strength was applied at a constant rate until failure (Figure 4a,b). Flexural strength was performed on prism specimens with dimensions of 100 × 100 × 400 mm in accordance with ASTM C78. The applied load was 1.0 MPa/min (Figure 4c).

The drying shrinkage was performed to evaluate the potential for concrete to shrink over time due to moisture loss in accordance to ASTM C157. The prism specimens with a size of 100 × 100 × 400 mm were mounted on a device with an electronic dial gauge after 24 h of curing, and placed in a chamber with controlled temperature and relative humidity set to 23 °C and 50%, respectively, for 100 days (Figure 4d).

The rapid chloride penetration test was performed according to ASTM C1202 to evaluate the resistance of concrete to chloride ions. Concrete disk samples with a size of 100 × 50 mm for testing were obtained by cutting the center of 100 × 200 mm cylindrical specimen, and the sides of the disk samples were coated with epoxy. The specimens were then conditioned according to the procedures specified in the standard: the specimens were placed in a vacuum desiccator at an absolute pressure of 6.65 kPa for 3 h, and water was put through the water valve to soak the specimens in water for 1 h under vacuum. The vacuum was then removed by opening the air valve and left in the water for 18 h. The conditioned specimens were assembled in a cell and applied at 60 V for 6 h (Figure 4e).

3. Results and Discussion

3.1. Workability

The slump values of the MRAC manufactured by the CMD and the EMV method are shown in Figure 5. The slump of NAC was 180 mm, and RAC1 achieved workability nearly comparable to that of NAC, regardless of the mix designs and the RCA1 replacement ratio: the slump values of R1-C-100, R1-E-50, and R1-E-100 were 180 mm, 170 mm, and 160 mm, respectively. However, as the number of recycling cycles increased from RAC1 to RAC2 and RAC3, a decrease in slump was clearly observed, which can be explained by the relationship between the quality of RCAs and the workability of RACs. The quality of the RCAs used in this study decreased with increasing number of recycling generations. That is, the water absorption and adhered mortar content increased in the order of RCA1, RCA2 and RCA3. The water absorption of RCAs reduces concrete slump by absorbing water during mixing, thus the increased absorption, along with the number of recycling cycles, can be considered a parameter causing the slump loss of concrete. These results are consistent with the trends reported in previous studies [8,26–28]. The slump loss was particularly noticeable in the concretes with the EMV design, including the modified one. Compared with R1-C, the slump losses of R2-C and R3-C were 17% and 56%, respectively, while at a given recycling generation, the slump losses of E-50 concretes were 53% and 71%, and those of E-100 concretes were 62% and 69%. This slump loss occurs due to the nature of the EMV design, in which the amount of fresh mortar is reduced by the volume of the adhered mortar attached to the RCA [29,30].

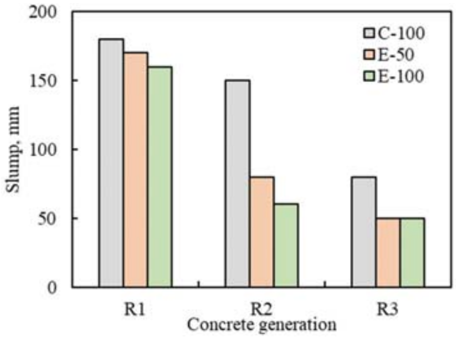

Figure 5. Slump of multiple recycled aggregate concrete.

3.2. Density and Water Absorption

The test results for density and water absorption are presented in Figure 6a,b. At 28 days, the density and water absorption of NAC were 2330 kg/m^3 and 4.75%, respectively, and those of MRAC varied from 2208 to 2372 kg/m^3 and from 2.87 to 7.61%.

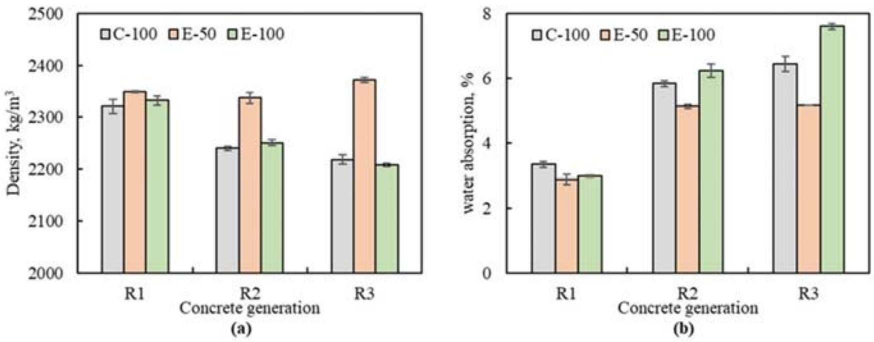

Figure 6. Density (**a**) and water absorption (**b**) of multiple recycled aggregate concrete.

The RAC1s showed little difference in density compared to NAC (≥1%). Furthermore, the densities of the RAC1s are almost similar to each other: 2321 kg/m^3 for R1-C-100, 2349 kg/m^3 for R1-E-50 and 2332 kg/m^3 for R1-E-100. This is related to the quality of the aggregate used, i.e., the density of RCA1 is comparable to that of NCA.

As the number of recycling generation increases, the density of C-100 concrete gradually decreases. The densities of R2-C-100 and R3-C-100 were 3.5% and 4.4% lower than that of R1-C-100. This reduction is a result of the increased accessible porosity due to the higher adhered mortar content and lower density of RCA with increasing number of recycling [15]. Unlike the EMV method, the CMD does not consider the characteristic variation of RCA, thus the mix proportions in each recycling generation are the same. As a consequence, the total mortar volume of the C-100 concretes increases and the volume of aggregate decreases as the number of recycling cycles increases. Given that the density of mortar is usually lower than that of aggregate, the result seems reasonable. In other words, the EMV method is based on the principle that the volume of aggregate and the volume of mortar constituting unit concrete are kept constant regardless of the adhered mortar content and replacement ratio of RCA [21]. However, contradictory results were observed between the E-50 series and the E-100 series. For the E-50 concretes, the variation in density with increasing number of recycling cycles was less than 1% (2350 kg/m^3 for RAC1, 2337 kg/m^3 for RAC2 and 2372 kg/m^3 for RAC3), whereas for the E-100 concretes, the density decreased by up to 5.3%. The combination of the EMV mix design with high volume and low-quality RCA often causes workability issues. Hayles et al. [31] noted that due to the lack of fresh mortar, the EMV-based concrete in the fresh state cannot be compacted properly as the cement paste does not sufficiently cover the aggregate, and this consequently increases the air content, thereby lowering the density of the concrete. Similarly, Kim at el. [17] reported that it was not possible to mold specimens of the EMV-based concrete with 100% RCA. This explains why the density of the E-100 concretes is lower than that of E-50 concretes.

Figure 6b shows the results of water absorption. The lowest and highest water absorption were observed in R1-E-50 and R3-E-100. Due to the effect of high-quality RCA1, the water absorption of C-100, E-50, and E-100 in the first generation were 3.34%, 2.87%, and 2.99%, respectively, with a difference of only 0.47% between the maximum and minimum values. However, in the second generation, the water absorption of each concrete increased to 5.84%, 5.13% and 6.24%, and the difference between the maximum and minimum values began to widen to 1.11% compared to that of the first generation concretes. In the third generation, the water absorption of C-100 and E-100 further increased to 6.44% and 7.61%, while that of E-50 tended to stabilize at 5.17% compared to 5.13% in the second generation. The difference between the maximum and minimum values was 2.44%, the largest compared to previous recycling generations. The results of water absorption are inversely proportional to those of density.

3.3. Mechanical Strength

The test results of the 28-day compressive strength, one of the most decisive properties of hardened concrete, are shown in Figure 7a,b. The compressive strength of NAC was 39.1 MPa, and that of the RACs varied from 31.5 MPa to 44.7 MPa.

The compressive strength of the first generation concretes, R1-C-100, R1-E-50 and R1-E-100, increased by 5% to 14% over that of NAC. This increase can be attributed to the quality of RCA1, which has low water absorption and high density. Concrete made with high-quality RCA exhibits comparable to or even better strength than concrete with NCA [27,28]. Specifically, the compressive strengths of the R1 concretes were similar at 43.4 MPa, 43.5 MPa, and 41.2 MPa, respectively, indicating that the influences of the mix designs and RCA replacement ratios were insignificant. This can be explained by the fact that the adhered mortar content of RCA1 (11%) is lower than that reported in the literature (about 25–55%) [27]; thus, the mix proportions do not differ significantly between the concretes designed by the CMD and the EMV method, resulting in similar strength.

The effects of the mix design methods are noticeably observed in RAC2 and RAC3. For the concrete with CMD, the compressive strength progressively decreases as the number of recycling cycles increases, as reported in previous studies [7,15]. The compressive strength of R2-C-100 and R3-C-100 was reduced by 6% and 25%, respectively, compared to R1-C-100 (Figure 7b). In contrast, for the EMV-based concretes, contradictory results were shown depending on the RCA replacement ratio. The compressive strength of E-100 concretes decreased with recycling number as observed for the C-100 concretes, with losses of 11% and 24% for the R2-E-100 and R3-E-100, respectively. However, for the E-50 concretes, the compressive strength of R2-E-50 decreased by only 3% compared to the R1-E-50, but that of R3-E-50 increased by 3%, showing that the number of recycling cycles has little effect on the E-50 concretes. The trend detected in the compressive strength results was also observed in the flexural strength (Figure 7c,d) and splitting tensile strength (Figure 7e,f). Namely, the C-100 and E-100 concretes showed a clear decrease in flexural and splitting tensile strength with increasing number of recycling cycles. From RAC1 to RAC3, the flexural and splitting tensile strength of the C-100 concretes were reduced by 8% and 16%, respectively, and those of E-100 concretes decreased by 17% and 16%. However, for the E-50 concretes, no consistent decreasing trend with the number of recycling cycles was observed. Compared to R1-E-50, the flexural strength decreased by 8% and 7% for R2-E-50 and R3-E-50, respectively, and the splitting tensile strength was reduced by 3% for R2-E-50, but increased by 5% for R3-E-50.

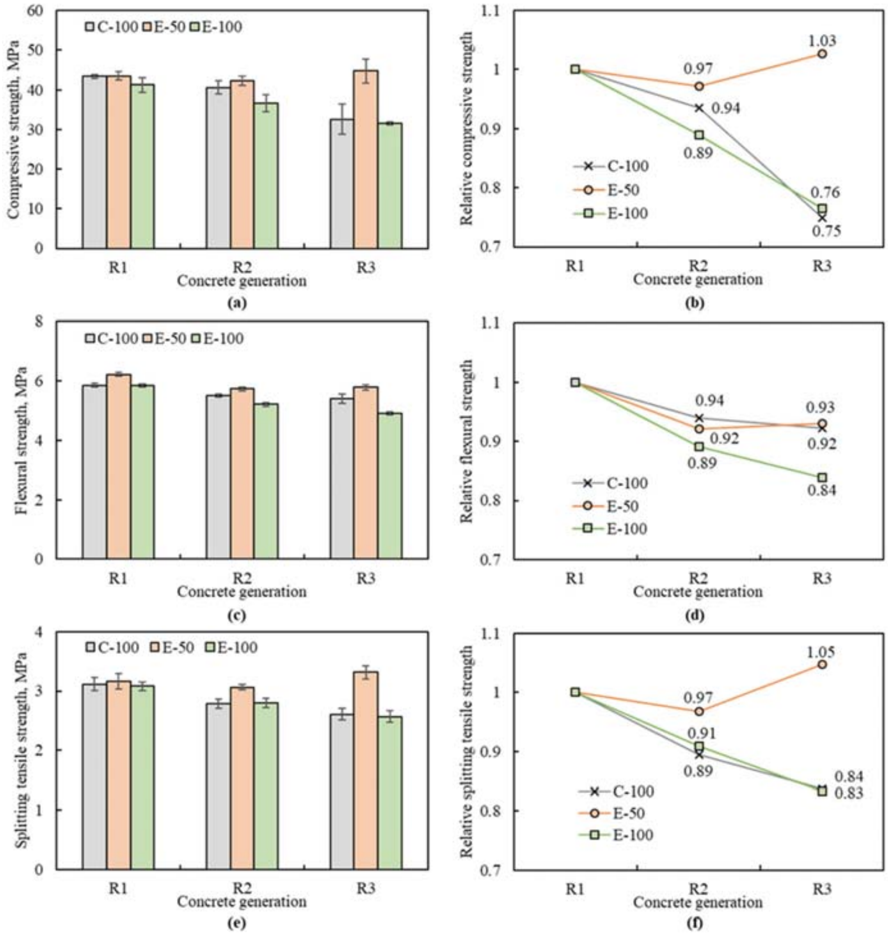

Figure 7. Mechanical strength of multiple recycled aggregate concrete: (**a**) compressive strength; (**b**) relative compressive strength; (**c**) flexural strength; (**d**) relative flexural strength; (**e**) splitting tensile strength; (**f**) relative splitting tensile strength.

The gradual decrease in mechanical strength observed in the CMD-based concretes is associated with changes in RCA characteristics. The RCAs experienced deterioration in quality, such as increased water absorption and decreased density, with the number of recycling cycles. This leads to a weaker ITZ between the RCA and cement paste, resulting in strength loss [8]. In contrast, several previous studies [23,32] have reported that the EMV-based concretes have higher mechanical strength than CMD-based concretes with NCA or RCA. This is consistent with the experimental results of the E-50 series in this study. However, the strength of the E-100 series was significantly lower than that of the E-50 series, even though the same mix design method was applied. This is because the E-50 concretes made of a combination of 50% NCA and 50% RCA have a smaller ITZ between the RCA and cement paste than C-100 and E-100, and thus have stronger resistance to external forces. In fact, Fathifazl et al. [22] stated that the total mortar volume in EMV concrete is not a determining factor for strength development. In addition, the shortage of fresh mortar causes poor workability, which is responsible for the density decrease and water absorption increase in the E-100 concretes. Nevertheless, it is noteworthy that the E-100 concretes showed nearly similar compressive strength to the C-100 concrete in the third generation and splitting tensile strengths in the second and third generation, despite containing 19% and 27% less cement content.

The mechanical strength test results indicate that high-quality RCA can replace natural aggregates in terms of concrete strength without any significant barriers. Furthermore, by combining the proper RCA replacement ratio and concrete mix design, strength loss caused by multiple recycling can be prevented.

3.4. Drying Shrinkage

The results of drying shrinkage on various concretes for 100 days are plotted in Figure 8. For all MRACs, drying shrinkage increased in a time-dependent manner. At 100 days, the NAC exhibited drying shrinkage of 313 μm, while the MRAC exhibited a range of 278 μm to 414 μm.

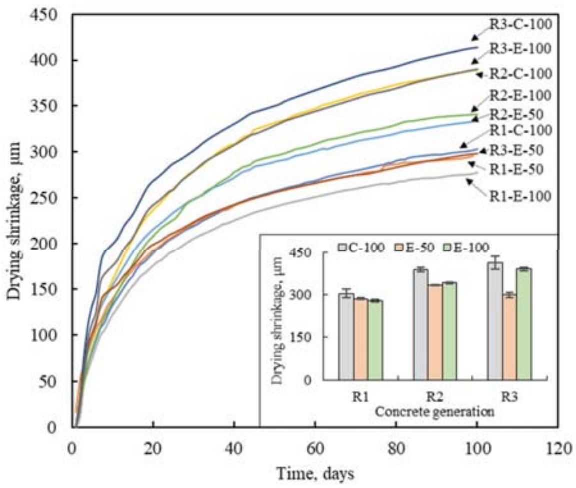

Figure 8. Drying shrinkage of multiple recycled aggregate concretes.

The drying shrinkage of the CMD-based concrete increased with the number of recycling cycles. Compared to R1-C-100, the drying shrinkage of R2-C-100 and R3-C-100 was 28.0% and 36.2% higher, respectively. This increase can be attributed to changes in the physical characteristics of the RCA as the number of recycling cycles increases. Previous studies [27,33] have found that the quality of RCA is one of the parameters affecting drying shrinkage of concrete. In general, high-quality RCA has less effect on concrete drying shrinkage than low-quality RCA. As the number of recycling increased, the RCA experienced a decline in quality with a progressive increase in adhered mortar content. The increase in the adhered mortar content lowers the stiffness of RCA and consequently makes concrete more susceptible to drying shrinkage deformation. The drying shrinkage results of the CMD-based concretes are consistent with those of a previous study [34]. At 100 days, compared to R1-E-50, the drying shrinkage of R2-E-50 increased by 16.8%, while that of R3-E-50 increased by 10.4%, showing 8.9% less shrinkage than R2-E-50. In addition, as shown in the bar graph in Figure 8, the effect of the number of recycling cycles on the drying shrinkage of E-50 concrete was not as great as that of C-100 and E-100 concretes. This may be because the volume of each raw material in the E-50 concretes is kept similar regardless of the recycling generation. Nevertheless, the E-100 series showed an increase in drying shrinkage with the number of recycling cycles. The 100-day drying shrinkage of R2-E-100 and R3-E-100 increased by 12.3% and 40.7%, respectively, compared to R1-E-100. The higher drying shrinkage of E-100 concretes can be attributed to their water absorption performance. The drying shrinkage occurs when moisture in the pores of concrete evaporates. Due to the higher water absorption capacity than that of R-E-50 concrete, R-E-100 concrete shrinks more in dry environments. In each recycling generation, the CMD-based concrete was determined to be more shrinkable than the EMV-based concrete. Specifically, as described in previous sections, due to the high quality of RCA1, the effect of mix design method and RCA replacement ratio on the drying shrinkage of the first generation concrete was not significant. However, their influence was prominent in the second and third generations. Compared to R2-C-100, the drying shrinkage of R2-E-50 and R2-E-100 decreased by 14.2% and 12.2%, respectively. Compared to R3-C-100, the R3-E-50 and R3-E-100 showed 27.9% and 5.6% lower shrinkage, respectively. The cement content is recognized as one of the key factors that determines drying shrinkage. In light of this, it is noteworthy that the EMV-based concrete with a low total mortar volume can effectively suppress drying shrinkage [35]. Yang and Lim [30] reported that for the EMV-based concrete, the drying shrinkage decreased with lower unit cement content when the water-cement ratio was the same.

3.5. Rapid Chloride Penetration Resistance

The results of electrical conductivity tests performed on each concrete are shown in Figure 9. Based on the amount of charge passed in coulomb, chloride ion permeability can be classified into five groups, and a higher value means a lower resistance to chloride ion penetration: negligible (<100 C); very low (100–1000 C); low (1000–2000 C); moderate (2000–4000 C); high (>4000 C). The charge passed for NAC was 3423 C, indicating a 'moderate' level of chloride permeability. The charge passed for MRAC ranged from 2826 C to 4878 C, which put most MRAC in the 'moderate' group, but R3-C-100 and R3-E-100 exceeded 4000 C, indicating a 'high' chloride permeability.

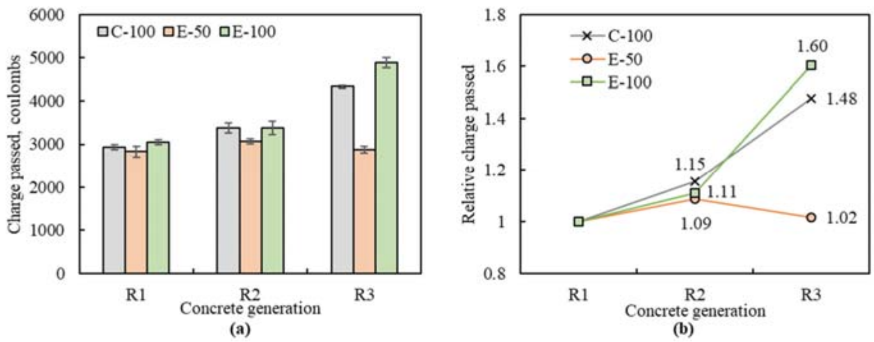

Figure 9. Electric conductivity of multiple recycled aggregate concretes: (**a**) electric charge passed; (**b**) relative electric charge passed.

Figure 9b shows the relative amount of charge passed during a total of three recycling of C-100, E-50 and E-100 concretes. Compared to the first generation, the charge of C-100 concretes increased by 15.4% and 47.7% in the second and third generations, respectively, indicating that the resistance to chloride penetration weakened with increasing number of recycling. This is related to the pore system of concrete, where the pores in the concrete matrix act as pathways to facilitate the movement of chloride ions [36]. With each generation, the increased adhered mortar content contains more microcracks and porosity, enabling more charges to pass through the concrete. Similar experimental results were reported by Zhu et al. [10]. For the EMV-based concretes, the amount of charge passed did not significantly change with recycling generations at 50% RCA replacement. To be specific, the amount of charge increased by only 8.6% and 1.7% in the second and third generations, respectively. This low variation can be attributed to the fact that the total mortar volume of the E-50 concrete remained constant in each generation, allowing for similar charge passed, as reported by Yang and Lee [18]. In addition, the presence of NCA in EMV-based concrete can contribute significantly to improving resistance to chloride ion penetration by segmenting the pores [37]. However, at 100% replacement ratio, the charge passed increased by 11.0% and 60.4% at the given generations. This is because E-100 concrete became less dense and more porous due to poor workability caused by the lack of fresh mortar as the number of recycling cycles increased. Therefore, to ensure chloride resistance in EMV-based concrete, the appropriate replacement range of RCA needs to be considered.

3.6. Comparison with Previous Studies and Discussion

To verify representativeness and effectiveness, the experimental data obtained in this study were compared with those of previous studies [7–10,26,34]. Figure 10 shows the variation in concrete properties as a function of the number of recycling cycles. In previous studies, a clear trend was identified where the compressive strength and tensile strength decrease and chloride penetration increases with increasing number of recycling, which is consistent with the results of the C-100 and E-100 concretes in this study. Using a lower volume of RCA (25%) could relatively compensate for the performance loss, but negative effects of multiple recycling were consistently observed [7,9,34]. On the contrary, the E-50 concrete did not exhibit a decreasing trend with the number of recycling, which demonstrates the effectiveness of the EMV method combined with a certain range of RCA replacement ratio.

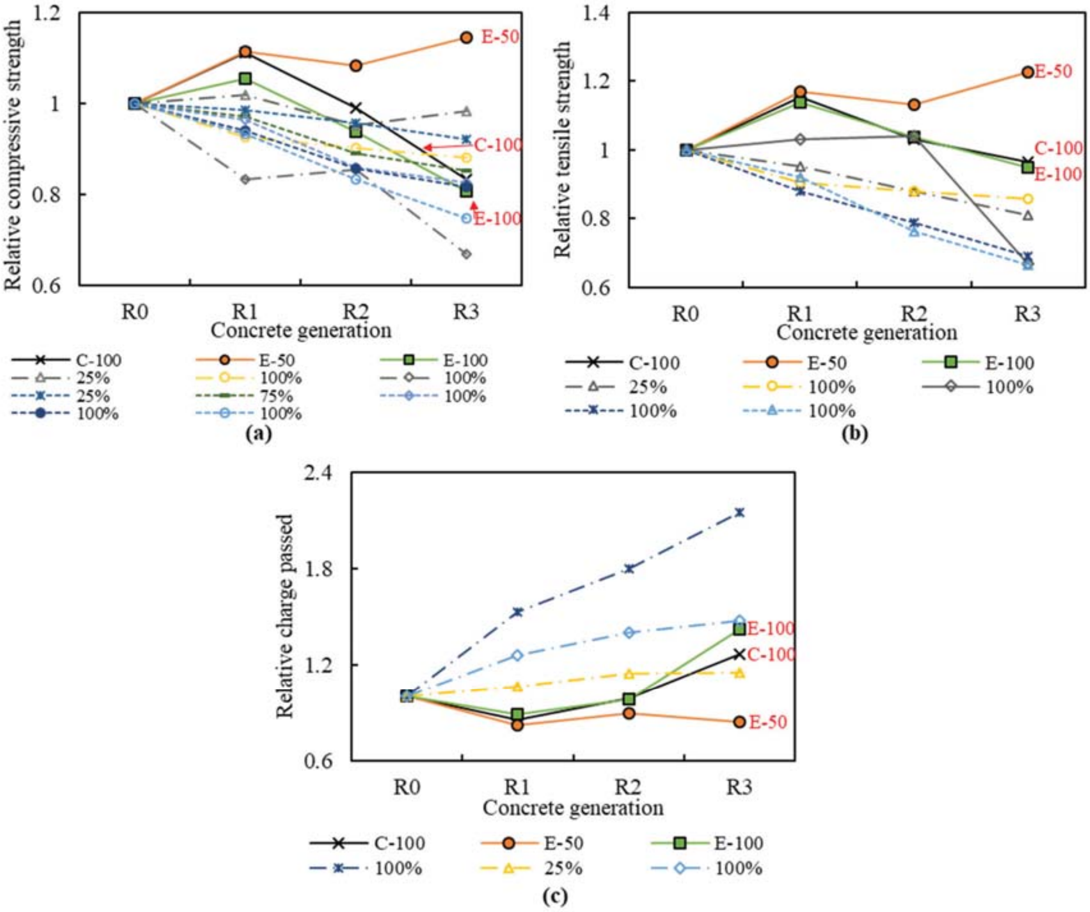

Figure 10. Comparison with previous studies: (**a**) compressive strength; (**b**) tensile strength; (**c**) chloride penetration [7–10,26,34].

The degradation of MRAC is associated to the gradual increase in the adhered mortar content of RCA obtained from repeated recycling of concrete, resulting in RCA turning into a low-density, high-porosity material. Figure 11 illustrates the relationship between the RCA water absorption and the compressive strength of concrete presented in previous studies and in the current study. Based on the trend line plotted in Figure 11, previous studies, and C-100 and E-100 concretes show that there is an inverse relationship between RCA water absorption and the compressive strength of concrete. In contrast, the fact that E-50 concrete exhibits similar strength values regardless of RCA water absorption indicates that it is not significantly affected by aggregate characteristics. This finding is particularly important in terms of utilizing low-quality RCA without degrading concrete performance. Moreover, this can provide important implications for the use of RCA in concrete. The requirements of RCA for concrete purpose vary greatly depending on the country and institution. According to Tam et al. [1], the RILEM, German and Hong Kong standards allow a maximum water absorption of 10% for RCA for concrete, whereas in Japan, the allowable water absorption for structural and non-structural concrete is 3% and 7%, respectively. Similarly, in Korea, the water absorption of RCA for concrete should not exceed 3%. Considering these requirements, when the strict standards of the latter countries are applied, multi-recycled RCA fails to meet the current standards required for use as RCA in concrete. This indicates that low-quality RCA should only be used for low-level recycling, such as backfilling and road subbase, despite its potential to achieve good performance as in the E-50 concrete. As the production of high-quality RCA is energy-intensive, it is necessary to explore ways to promote the use of low-quality RCA through research that integrates various parameters, and to establish technical guidelines for the use of multi-recycled aggregates.

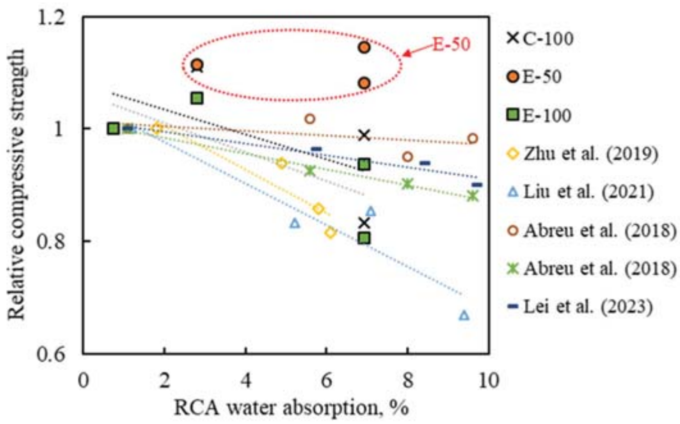

Figure 11. Correlation between RCA water absorption and compressive strength [7,8,10,11].

4. Conclusions

In this study, various properties of MRAC designed by the CMD and the EMV method were investigated.

- Concrete that includes RCA1 with low water absorption demonstrated performance comparable or superior to NAC. The slump of R1 concretes ranged within ±20 mm, and properties such as compressive strength (5–11%), tensile strength (±3%), flexural strength (14–17%), chloride resistance (11–18%), and drying shrinkage (3–12%) were improved when compared to those of NAC. This indicates that the poor performance caused by RCA in concrete compared to NCA can be offset by the use of high-quality RCA.
- As the number of recycling processes increases, the quality of RCA gradually diminishes, leading to a significant deterioration in the properties of the resulting concrete. Compared to R1-C-100 and R1-E-100, the slump, mechanical strength, and chloride

resistance of R3-C-100 and R3-E-100 concretes decreased by up to 69%, 25%, and 60%, while the drying shrinkage increased by 40%. However, in contrast to this trend, the E-50 concretes exhibited a similar level of performance across three generations of recycling. Therefore, it can be concluded that the use of multi-recycled aggregate may reduce the performance of concrete, but this performance degradation can be mitigated through a combination of appropriate mix design and RCA replacement ratio.

- The experimental results in this study also indicate that RCA, even multiple RCA, have no barriers to being used as substitutes for NCA in terms of concrete performance. This could be an important finding in achieving true sustainability, enabling repeated recycling of concrete.
- Irrespective of the mix design method, remarkable slump losses were observed as the number of recycling increased, particularly in case of the EMV-based concrete. For the E-50 concrete, despite the good hardened performance, it may not suitable for building concrete unless its workability is improved. On the other hand, due to its low slump, the E-50 concrete can be utilized for prefabricated concrete elements, such as road pavement, precast structural members, sewage pipes, bricks and blocks.
- Since the concept of multiple recycling of concrete has been discussed relatively recently, there are many unknowns compared to the 'used once' recycled aggregate concrete. Therefore, further research is needed from various perspectives. For example, an investigation could be conducted to overcome the observed slump loss of MRAC through an increase in plasticizer dosage or through the use of supplementary cementitious materials. In addition, chemical and microstructure analyses, which have not been performed in this study, are recommended. Particularly, the analysis on the economic viability and environmental impact of multiple recycling of concrete remains unexplored, which will make a significant contribution towards achieving true sustainability in the concrete industry.

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An Experimental Study on Structural Concrete Containing Recycled Aggregates and Powder from Construction and Demolition Waste

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Abstract: For complete utilization of construction and demolition (C&D) waste, an investigation of all size fractions of C&D waste generated during the recycling process should be conducted. In this work, the effects of three recycled concrete materials with different sizes (recycled coarse aggregate (RCA) with a size of 4.75–25 mm, recycled fine aggregate (RFA) of 0.15–4.75 mm, and recycled powder (RP) smaller than 0.15 mm) produced from concrete waste on the fresh and hardened mechanical properties of concrete were evaluated. The replacement ratios of natural coarse and fine aggregates by RCA and RFA were 30, 60, and 100%, and those of ordinary Portland cement for RP were 10, 20, and 30%. The results showed that the concrete properties deteriorated with increasing replacement ratio regardless of the type of recycled materials. The properties were reduced in the order of the use of RFA, RCA, and the simultaneous use of RCA and RFA. In addition, concrete with 30% RP showed lower mechanical strength than concrete with 100% RCA and 100% RFA. However, all concretes could be applicable for structural purposes under different environmental exposure conditions. In particular, concretes with 10% RP and 20% RP showed better cost-benefits compared to natural aggregate concrete with 100% ordinary Portland cement. These promising findings provide valuable initiatives for the effective and complete recycling of C&D waste.

Keywords: recycled coarse aggregate; recycled fine aggregate; recycled powder; recycled aggregate concrete; construction and demolition waste

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1. Introduction

The evidence for the loss of stability of the Earth's natural climate system, especially in view of the increase in the frequency of extreme weather phenomena including global warming, despite the debate over their actual causes (solar activity, Milankovitch cycles, volcanic activity, and El Niño Southern Oscillation phenomenon) is difficult to contest. However, the most probable main cause is the growing increase of carbon dioxide (CO_2) in the atmosphere, mainly due to anthropogenic activities. One of the areas of human activity involved in the increase of CO_2 emission is the concrete industry. Despite the efforts of several researchers, such as carbon-friendly design and extending the lifecycle of structures to reduce CO_2 emissions [1,2], there is no doubt that concrete will remain a basic construction material for a long time. Unfortunately, its production focused on high quality imposes a heavy burden on the environment. A major contributor to the environmental impact for energy consumption and emission of greenhouse gases, including CO_2, is the production of cement, the key constituent of concrete. According to Andrew [3], the global CO_2 emissions accompanying the cement production in 2016 were estimated at 1.45 ± 0.20 Gt CO_2. However, other technological operations related to the production of concrete, from the extraction of natural resources (natural aggregates, raw materials for processing into crushed aggregates, raw materials necessary to produce cement), their transport, through mixing the components of the concrete mixture, its laying and compaction, including concrete care as well as the use and maintenance of buildings until the last stages of their life, also make a significant contribution to the anthropogenic CO_2 emissions [4].

It is also important to note that the deposits of natural resources are depleting. Their place in natural space is taken by waste materials from various production, the effect of which is a violation of ecological systems [3]. The main source of waste generated in the world is construction activities. Construction and demolition (C&D) waste in 40 countries reached more than 3 billion tons per year [5], and China and the United States are reported to be responsible for about 30% of the global C&D waste generation [6]. Furthermore, many studies have shown that C&D waste accounts for 30–50% of the total waste generated worldwide, and the amount of C&D waste is gradually increasing annually [7–9]. Therefore, it is rational to reutilize C&D waste, particularly from concrete, such as recycled coarse aggregate (RCA), recycled fine aggregate (RFA), and recycled powder (RP), even using repeated crushed recycled aggregate [10–12]. The performance of concrete with recycled aggregates is obviously worse. However, when asked what is more important, the performance of the concrete which can be improved in various ways, or environmental protection for ecological reasons, understood in a wide range, the second approach is more justified.

In this context, the recyclability of C&D waste has been investigated. One of the applications considered as advanced recycling is the replacement of natural materials with recycled materials in concrete production. In general, three recycled concrete materials can be obtained from C&D waste, depending on the particle size, i.e., RCA, RFA, and RP (hereinafter the recycled concrete materials in this paper refer to RCA, RFA, and RP).

RCA, which occupies the largest volume in concrete, has received the most attention from researchers as a substitute for natural coarse aggregates (NCA). In addition, technologies and methods for improving the performance of recycled aggregate concrete (RAC) have been developed mainly based on RCA. Therefore, the knowledge system on the effects of RCA on concrete is well-established [13,14], and guidelines for the use of RCA have been suggested by several countries [8,15,16]. Some researchers pointed out that research on concrete recycling has been relatively limited to RCA [17,18]. RFA as a substitute for river sand and natural fine aggregate (NFA) has received relatively less attention compared to RCA. Recent environmental issues, such as restrictions on sand mining in some areas for ecosystem protection, urge the use of RFA. In the past, the use of RFA in concrete was restricted due to concerns about material contamination and difficulties in quality control [19], but recent studies have reported that RFA does not seriously affect the mechanical and durability properties of concrete within an appropriate replacement ratio [20–22]. Replacing both NCA and NFA with RCA and RFA can yield higher energy and resource savings because a greater amount of recycled concrete materials produced can be used, but the simultaneous use of RCA and RFA has a more negative impact than the use of a single type of the recycled concrete material. In a study performed by Pedro et al. [23], the 28-day compressive strength of concrete made with 100% RCA and concrete made with 100% RFA was 5.4% and 9.9% lower than that of control concrete, respectively, whereas that of concrete with 100% RCA and 100% RFA decreased by 14.9%. Although some previous studies have been published [23,24], the simultaneous incorporation of RCA and RFA into concrete is still a new area in which limited scientific research has been conducted. Therefore, the obtained results have important implications both in terms of scientific and practical use. Lifecycle assessment showed that cement production was the largest contributor in all environmental impact categories, irrespective of natural aggregate concrete (NAC) and RAC [25,26]. Hence, reducing cement consumption is a clear alternative to reducing CO_2 emissions in the concrete industry. Accordingly, several studies have investigated the effectiveness of various supplementary cementitious materials, such as glass powder and fly ash, to decrease cement usage [27,28]. However, RP as a supplementary cementitious material is arguably the least investigated material compared to RCA and RFA [18]. In the concrete matrix, RP acts as a filler that fills the pores of the concrete and makes it compact, but on the other hand, the low reactivity of RP does not contribute to strength development by forming fewer hydration products, which is the cause of the low performance compared to concrete made of Portland cement.

In this context, the transition to the 'zero-waste' pursued by today's society in the construction sector cannot be achieved without a systematic discussion of the influence of recycled concrete materials of all size fractions generated from C&D waste. As described above, several studies have been conducted on the application of RCA, RFA, and RP as concrete materials, but these studies discuss the properties of concrete using materials obtained from different C&D waste sources or using two recycled concrete materials, mainly RCA and RP [29–31]. Particularly, little research has been carried out on the properties of concrete incorporating RCA, RFA, and RP obtained from a single source of concrete waste. Thus, this study aims to fill the gap in scientific and technical understanding of the behavior of concretes which incorporate recycled concrete materials with various size fractions obtainable by C&D waste recycling. To achieve this objective, the effect on fresh and hardened mechanical properties of concretes made from each recycled material at various replacement ratios was investigated. The fresh-state properties studied included slump and air content, and the hardened properties were evaluated for compressive strength, tensile strength, and elastic modulus. Subsequently, the correlations between the hardened properties were compared with prediction models presented in the literature. In the end, the economic and environmental benefits of each mix were analyzed. This study can provide valuable insights on the economical and eco-friendly use of recycled concrete materials obtained from C&D waste for structural concrete.

2. Materials and Methods

2.1. Materials

The RCA, RFA, and RP used in this study were obtained by crushing intentionally produced NAC. This NAC serves both as a parent concrete for obtaining recycled concrete materials and as a reference concrete (RC) for property comparison. Natural granitic crushed aggregate with a nominal maximum aggregate size of 25 mm and siliceous river sand were used as NCA and NFA for the production of parent concrete. The specific gravity and water absorption of NCA were 2.68 and 0.88%, respectively, and those of NFA were 2.6 and 0.91%. Ordinary Portland cement (OPC) with a specific gravity of 3.14 and a specific surface area of 3550 cm^2/g was used as a cementitious binder. The composition of RC is provided in Table 1. The target strength and target slump of RC were 30 MPa and 100 mm, respectively.

Table 1. Mix proportion of reference concrete.

Mix	OPC (kg/m^3)	Water (kg/m^3)	w/c	NCA (kg/m^3)	NFA (kg/m^3)
RC	389	175	0.45	1011	740

At 56 days of age, the RC specimens after the testing described in Section 2.3 were compressed with a hydraulic universal testing machine and crushed into large pieces (approximately 50 to 100 mm in length), and these concrete fragments were crushed into sizes (up to 25 mm) suitable for concrete production using the Los Angeles ball mill. By combining mechanical and manual sieving, three recycled concrete materials with different size fractions were obtained: RCA with a size of 4.75–25 mm, RFA with a size of 0.15–4.75 mm, and RP smaller than 0.15 mm [32]. Table 2 shows the properties of recycled aggregates along with natural ones. RCA and RFA are less dense than NCA and NFA due to their greater porosity, resulting in higher water absorption. Figure 1 plots the particle size distribution curves for each aggregate.

Table 2. Physical properties of aggregates.

Aggregates	Specific Gravity	Water Absorption (%)
NCA	2.68	0.88
RCA	2.41	4.45
NFA	2.60	0.91
RFA	2.22	5.38

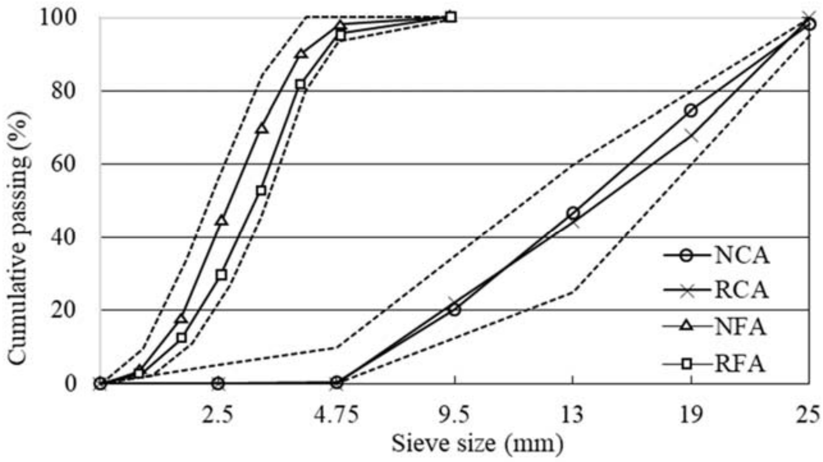

Figure 1. Particle size distribution of natural and recycled aggregates.

2.2. Mix Design and Testing Methods

To investigate the influence of RCA, RFA, and RP on the mechanical performance of concrete, 12 different concrete mixtures were prepared based on the ACI mix design [33]. According to [15], several regulations suggest that recycled aggregates (mainly recycled coarse aggregate) can replace about 20% up to 100% of natural aggregates. In addition, RCA can replace up to 60% of NCA when RCA is the only recycled material in concrete. When using RCA and RFA simultaneously, up to 30% of the total aggregate can be replaced [8].

Therefore, in this study, the replacement ratios of 30%, 60%, and 100% were applied. The description and notation for each mixture are as follows:

- RCAC-replacement ratio: concrete made from NCA, NFA, OPC, and RCA that replaces NCA in a certain ratio (i.e., 30%, 60%, and 100%).
- RFAC-replacement ratio: concrete made from NCA, NFA, OPC, and RFA that replaces NFA in a certain ratio (30%, 60%, and 100%).
- RPC-replacement ratio: Concrete made with NCA, NFA, OPC, and RP that replaces OPC in a certain proportion (10%, 20%, and 30%). Test results for RPC were adopted from the previous study of the author [32].
- RCFAC-replacement ratio: Concrete made by replacing both NCA and NFA with RCA and RFA in a certain percentage (30%, 60%, and 100%). OPC was used as a binder.

All concrete mixes had a constant quantity of 389 kg/m^3 binder (i.e., sum of OPC and RP), and the water-to-cement (w/c) ratio was fixed at 0.45. Details of the mix proportions of concrete are shown in Table 3.

Since the moisture state of aggregates is one of the parameters influencing the properties of concrete, the moisture condition of each aggregate was considered before mixing. Due to the high water absorption of RCA, pre-wetting is required to obtain proper workability. However, RCA in the saturated surface dry (SSD) state did not produce a favorable effect in terms of mechanical properties of concrete [34,35]. On the other hand, for RFA, the results of previous studies have reported that fine aggregate in the SSD state was more favorable to the mechanical strength of concrete than in the air-dry and oven-dry state [36,37]. Therefore, NCA, NFA, and RFA were used in the SSD state, and partially saturated RCA dried at room temperature 24 h before mixing after complete saturation was used [38].

Table 3. Mix proportions for concrete with recycled aggregates and recycled powder.

Mix Designation	OPC (kg/m^3)	RP (kg/m^3)	Water (kg/m^3)	w/c	NCA (kg/m^3)	RCA (kg/m^3)	NFA (kg/m^3)	RFA (kg/m^3)
RCAC-30	389	0	175	0.45	707	279	740	0
RCAC-60	389	0	175	0.45	404	545	740	0
RCAC-100	389	0	175	0.45	0	909	740	0
RFAC-30	389	0	175	0.45	1011	0	518	189
RFAC-60	389	0	175	0.45	1011	0	296	379
RFAC-100	389	0	175	0.45	1011	0	0	632
RPC-10 [32]	350	39	175	0.45	1011	0	740	0
RPC-20 [32]	311	78	175	0.45	1011	0	740	0
RPC-30 [32]	272	117	175	0.45	1011	0	740	0
RCFAC-30	389	0	175	0.45	707	279	518	189
RCFAC-60	389	0	175	0.45	404	545	296	379
RCFAC100 [32]	389	0	175	0.45	0	909	0	632

A mechanical pan mixer with a capacity of 60 L was used for the mixing of concrete components. Coarse and fine aggregates were put in a mixer and mixed for 30 s, then OPC was added and mixed for 90 s to disperse the material. Water was then added and mixed for 2 min. After the mixing process, the fresh properties of the concrete were evaluated, and specimens for evaluating the mechanical properties of the concrete were made in 100 × 200 cylindrical molds as per ASTM C192 [39]. The specimens were demolded 24 h after casting and cured in a container with tap water of 20 °C right before testing. Mechanical properties were measured using a hydraulic universal testing machine. Compressive strength and elastic modulus were measured at 28 and 56 days, and splitting tensile strength was measured at 28 days. Table 4 summarizes test types, standards, specimen sizes, and test ages.

Table 4. Summary of testing protocol.

Test	Standard	Specimen Size (mm)	Test Age (Days)
Fresh state			
Air content	[40]	n/a	Immediately after mixing
Consistency	[41]	n/a	Immediately after mixing
Hardened state			
Compressive strength	[42]	Ø100 × 200	28 and 56
Splitting tensile strength	[43]	Ø100 × 200	28
Elastic modulus	[44]	Ø100 × 200	28 and 56

2.3. Cost and Environmental Impact Assessment

A cost and an environmental impact assessment analysis were performed on the investigated concretes. The manufacturing cost per cubic meter (UDS/m^3) of each concrete was calculated based on the raw material price surveyed by the Construction Association of Korea as of November 2021 (Table 5). Based on the 28-day compressive strength test results, the strength–cost value analysis of each mix was discussed.

Based on the mix proportions, the global warming potential (GWP) of each mix was assessed. In Table 5, CO_2 equivalent emissions per kilogram (kg CO_2-eq./kg) from the manufacture of concrete components are presented and the values have been taken from [24,45,46].

Table 5. Unit price and global warming potential of concrete components.

Materials	Unit Cost (USD/ton)	GWP (kg CO_2-eq./kg)
OPC	103.75	0.931 [46]
RP	4.15	0.2457 [46]
NCA	8.67	0.0244 [45]
NFA	9.58	0.025 [45]
RCA	4.15	0.00744 [45]
RFA	6.64	0.012 [24]

3. Results and Discussion

3.1. Fresh Properties

Figure 2 shows the results of the slump test for RCAC, RFAC, and RCFAC at replacement ratios of 30%, 60%, and 100%, and those for RPC at replacement ratios of 10%, 20%, and 30%. Some mixes (RCAC-30, RFAC-60, RPC-10) showed the same slump value of 105 mm as RC, but overall, the slump was on a downward trend as the replacement ratio of each recycled concrete material increased. This result was generally observed in previous studies that investigated concrete containing recycled aggregates and RP, and is due to the high water absorption of recycled concrete materials compared to natural materials [47]. For each type of concrete mix, the maximum slump loss was observed at a replacement ratio of 100% (30% for RPC). In comparison with RC, the slump loss of RCAC and RFAC was up to 10%, and that of RCFAC was 14%. The slump of the concrete mix containing RP decreased by 10% and 19% at the replacement ratios of 20% and 30%, respectively, showing greater slump loss than RCAC, RFAC, and RCFAC. This may be because, unlike aggregates to which pre-wetting was applied, the moisture state of RP was not considered. Nevertheless, all mixes were within the tolerance of ±25 mm for concrete with a target slump of 100 mm according to ASTM C94 [48] (i.e., from 75 to 125 mm). Therefore, in order to obtain workability similar to that of RC, moisture compensation such as pre-wetting and the addition of mixing water should be considered.

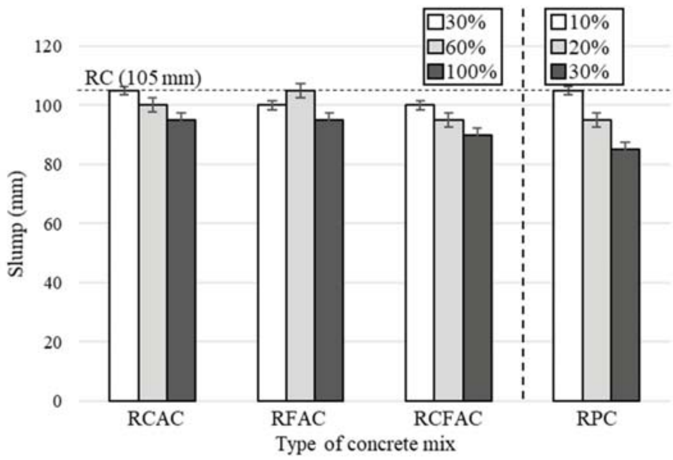

Figure 2. Slump test of concrete mixes made of recycled aggregates and recycled powder.

The test results for the air content of the concrete mixes are shown in Figure 3. The measured air content was within the tolerance of 4.5% ± 1.5% according to the ASTM C94 [48]. The air content of RC was 3.8%, and the concretes used with recycled concrete materials exhibited higher air content than the RC due to the porosity of the recycled materials. RFAC showed a relatively low increase in air content compared to RCAC and RPC. This is because the pores of RFA used in SSD conditions were filled with water, contributing to suppression of the increase in air content [49].

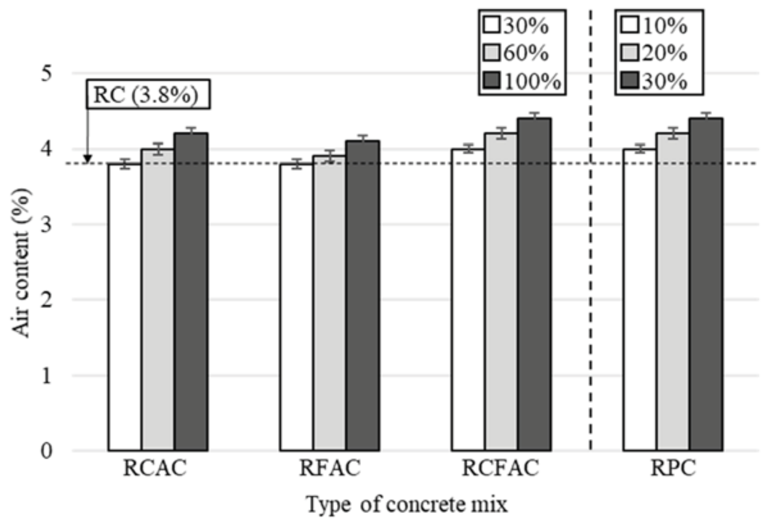

Figure 3. Air content of concrete mixes made of recycled aggregates and recycled powder.

3.2. Hardened Properties

3.2.1. Compressive Strength

The 28- and 56-day compressive strengths for different types of concrete incorporating each recycled concrete material are shown in Figure 4. The replacement ratios for RCAC, RFAC, and RCFAC were 30, 60, and 100%, while those of RP were 10, 20, and 30%.

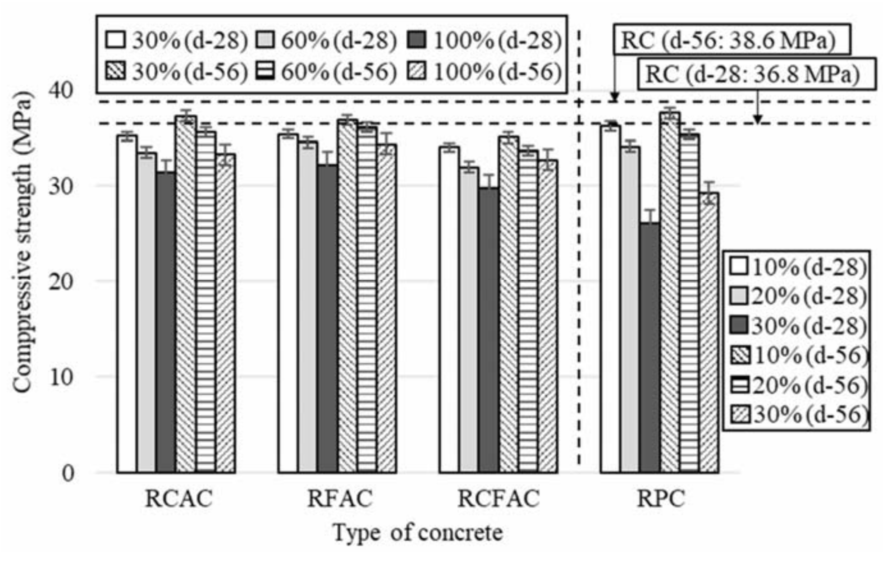

Figure 4. Test results of compressive strength of concretes made of recycled aggregates and recycled powder.

The experimental results have shown that the addition of recycled concrete materials reduces compressive strength regardless of the type of recycled material. This is in line with the general consensus of previous studies that the use of recycled concrete materials has a negative effect on the mechanical properties of concrete [50–53]. In comparison to RC, concretes with 30%, 60%, and 100% RCA showed 4%, 9%, and 15% losses in compressive strength at 28 days, respectively, and the losses at 56 days were 3%, 8%, and 14%. The reduction in compressive strength by replacing NFA with RFA was slightly lower than when replacing NCA with RCA. The 28-day compressive strength of RFAC was 4%, 6%, and 12% lower than that of RC at 30%, 60%, and 100% replacement ratios, but 0.2, 1.1, and 0.8 MPa higher than that of RCAC. This may be because the volume occupied by fine aggregates in unit concrete is smaller than that of coarse aggregates. However, there are conflicting results as to which of RCA or RFA has a more dominant effect on the poor performance of concrete. A greater loss of strength was observed in concrete with RCA than in concrete with RFA in some studies [54–56], and vice versa in other studies [17,23].

For concrete incorporating RP, the difference in compressive strength between RPC-10 and RC was 0.5 and 1 MPa at 28 days and 56 days, which is only 1% and 3% lower than that of RC. This insignificant variation was attributed to the filling effect, whereby RP, which is finer than NFA, fills the micropores, where the concrete becomes more compact and dense, reducing internal stresses and early crack propagation [57]. However, as the RP content increases, the negative effects of reduced hydration products outweigh the positive effects of filling [58]. The compressive strength of concrete with 20% RP as a cement binder was lower than that of RCAC-60, RFAC-60, and RCFAC-30. In addition, the maximum loss of compressive strength for all concretes investigated was observed in RPC-30, and the losses were 29% and 24% at 28 days and 56 days, respectively. This is in the range of losses reported in the studies of Xiao et al. [51] (7.7% reduction in strength at 30% RP replacement ratio) and Cantero et al. [59] (40% decrease in strength at 25% replacement ratio).

Figure 5 shows the behavior of the relative compressive strength of concretes made from different recycled concrete materials as a function of the replacement ratio. The strength decreased in the order of RCAC, RFAC, and RCFAC at the same replacement ratio. Concrete with simultaneous incorporation of RCA and RFA has a greater loss of compressive strength than concrete with RCA or RFA, which can be clearly seen in Figure 5. At a 100% replacement ratio, the compressive strength of RCAC, RFAC, and RCFAC decreased by 12–19%. This value is similar to or slightly lower than the loss reported in previous studies [21,23,54,56]. Khatib [21] reported a 36% reduction in compressive strength in concrete made with 100% RFA, and Guo et al. [54] reported a strength loss of up to 42.2% in concrete using both 100% RCA and 100% RFA. On the other hand, Cabral et al. [56] reported that the simultaneous use of 100% RCA and 100% RFA reduced the compressive strength by only 6–19%, and Pedro et al. [23] also reported a similar decrease in strength of 8–16%.

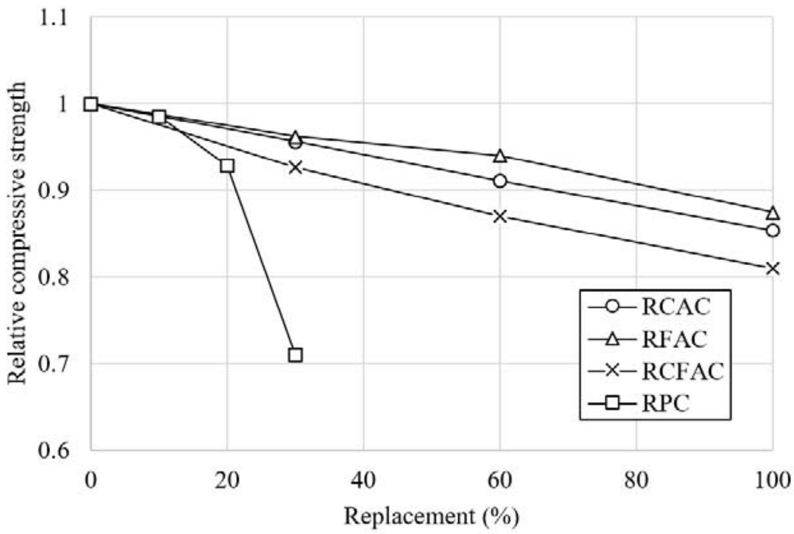

Figure 5. Relative compressive strength of various concretes by replacement ratio.

Table 6 briefly summarizes the minimum required compressive strength of concrete by environmental exposure classes specified in PN-EN 206:2016 [60]. With the increase in compressive strength, concrete can be applied in moderate to aggressive environments. Concrete with a compressive strength of less than 8 MPa cannot be used in environments where there is a risk of corrosion, whereas concrete with a compressive strength of over 35 MPa can be used as structural concrete in very harsh environments with constant or frequent exposure to seawater, carbonation, and sulfates. Among the concretes investigated in this study, RC, RCAC-30, RFAC-30, and RPC-10 mixtures can be used in all environments, and RCAC-60, RCAC-100, RFAC-60, RFAC-100, RCFAC-30, RCFAC-60, and RPC-20 are feasible options as structural concrete under no seawater exposure. RPC-30, which has the lowest compressive strength of 26.1 MPa, can also be used as structural concrete under moderate freezing-and-thawing attack.

Table 6. Environmental exposure conditions based on compressive strength of concrete.

Concrete Grade	Exposure Class *	Applicable Mix
C8/10	X0—no risk of corrosion	-
C16/20	XC1—dry or permanent wet XC2—wet, rarely dry	-
C20/25	XC3—moderate humidity XC4—cyclic wet and dry	-
C25/30	XF2—moderate water absorption (saturation), water includes de-icing agent	RPC-30 RCFAC-100
C30/37	XD1—moderately wet XD2—wet, occasionally dry XS1—action of salts in air = atmosphere XF1—moderate water absorption (saturation) XF3—strong water absorption (saturation), water without de-icing agent XF4—strong water absorption (saturation), water includes de-icing agent XA1—weak chemical aggression XA2—moderate chemical aggression XM1—moderate risk of abrasion	RCAC-60 RCAC-100 RFAC-60 RFAC-100 RPC-20 RCFAC-30 RCFAC-60
C35/45	XM2—strong risk of abrasion XD3—moderately wet and dry XS2—permanent immersion in water XS3—tidal, splash and aerosol zones XA3—strong chemical aggression XM3—extreme risk of abrasion	RC RCAC-30 RFAC-30 RPC-10

* X0—no risk of corrosion; XC—corrosion caused by carbonation; XD—corrosion caused by chloride except sea water chloride; XS—corrosion caused by sea water chloride; XF—freezing–thawing attack; XA—chemical attack; XM—abrasion.

3.2.2. Splitting Tensile Strength

The test results for splitting tensile strength at 28 days are presented in Figure 6. The results showed a similar trend to the compressive strength test result. That is, regardless of the concrete type, splitting tensile strength decreased as the content of recycled concrete materials increased. The 28-day splitting tensile strength of RC was 2.78 MPa, and those of recycled concretes varied (between 2.4 and 2.65 MPa for RCAC, 2.5–2.77 MPa for RFAC, 2.32–2.56 MPa for RCFAC, and 1.96–2.66 MPa for RPC). The loss of tensile strength in concrete made from RCA and RFA, which is low-strength and porous compared to NCA and NFA, is caused by poor bonding in the interfacial transition zone between the aggregate and cement paste [61]. On the other hand, for RPC, a decrease in strength with RP content occurs because RP, which has lower reactivity than cement, does not contribute to the strength development of concrete [62].

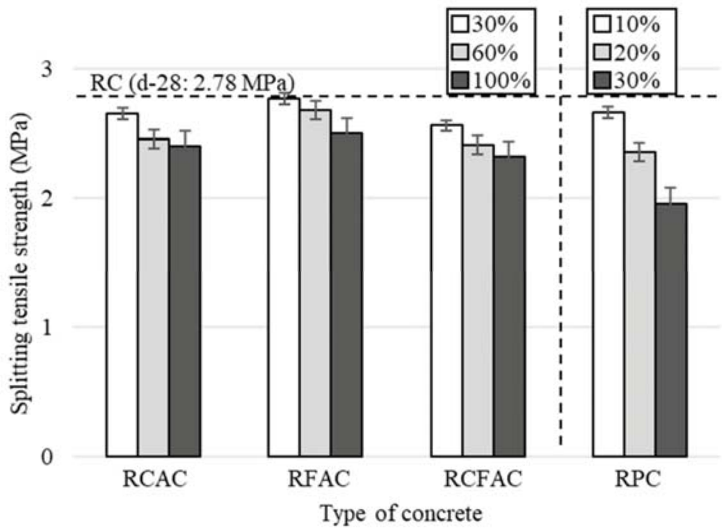

Figure 6. Test results of splitting tensile strength of concretes made of recycled aggregates and recycled powder.

Figure 7 shows the relative splitting tensile strength of concretes as a function of the replacement ratio. At the same replacement level, the strength decreased in the order of RFAC, RCAC, and RCFAC, with reductions of 5–14%, 0–10%, and 8–16%, respectively, in comparison with RC. Therefore, RCA seems to have a more negative effect on the tensile strength of concrete than RFA. The maximum reduction in tensile strength was observed for RCFAC-100, the concrete incorporating 100% RCA and 100% RFA simultaneously, which is consistent with the results of a previous study conducted by Singh et al. [17].

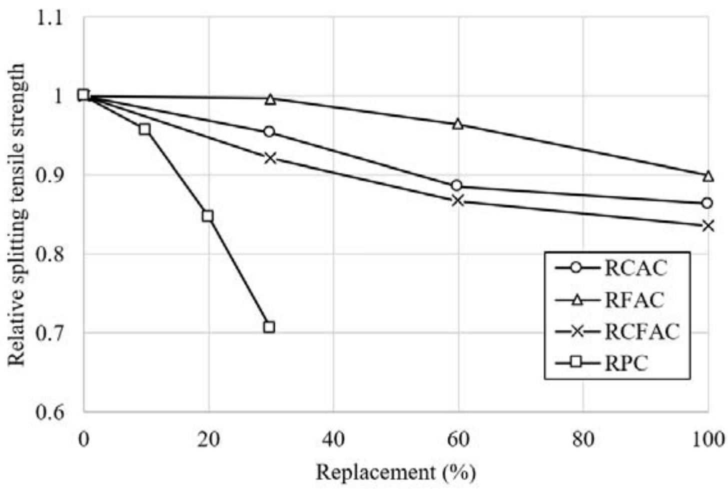

Figure 7. Relative splitting tensile strength of various concretes by replacement ratio.

The addition of 10% RP did not seem to have a significant effect on the splitting tensile strength of concrete. However, when 20% RP was added, tensile strength dropped sharply and showed similar strength to that of RCFAC-100. The tensile strength loss of RPC observed in this study was 4–29%, which is in good agreement with the values reported in previous literature. Cantero et al. [59] reported a decrease in tensile strength of 19.9% at 25% RP replacement, and Xiao et al. [51] and Kim [62] reported reductions of 10.6% and 21%, respectively, at the 30% replacement rate.

3.2.3. Elastic Modulus

The test results of the elastic modulus of concretes at 28 and 56 days are presented in Figure 8, and Figure 9 shows the relative elastic modulus at 28 days.

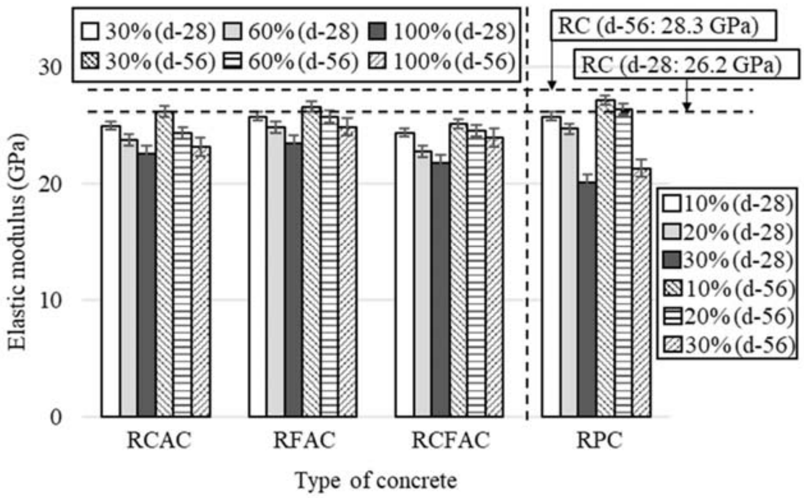

Figure 8. Test results of elastic modulus of concretes made of recycled aggregates and recycled powder.

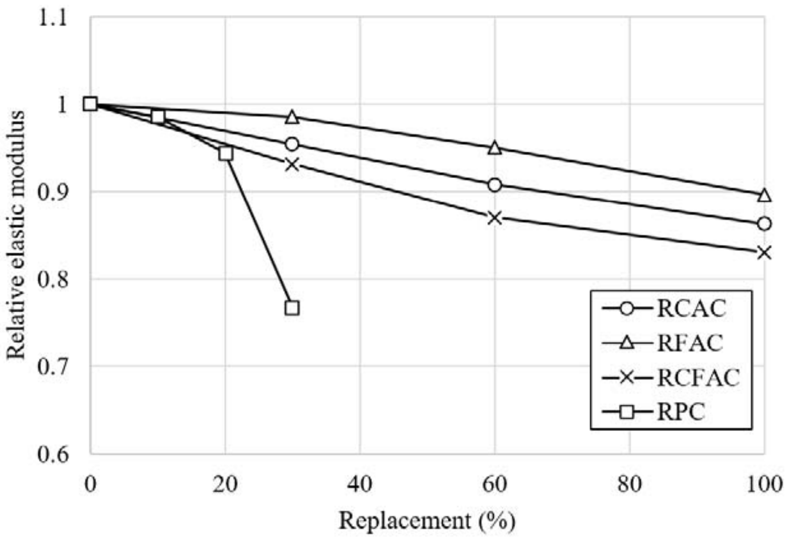

Figure 9. Relative elastic modulus of various concretes by replacement ratio.

Since the elastic modulus of concrete is closely related to the stiffness of the aggregate, porosity, and bonding of mortar, Evangelista and de Brito [63] noted that low levels of RA replacement do not cause a significant loss of elastic modulus. This supports that RFAC has the lowest modulus loss because it has the smallest volume of recycled material replacing natural materials in unit concrete. Compared to RC, the elastic modulus of RFAC decreased by 2–10%, while RCAC and RCFAC decreased by 5–14% and 7–17%, respectively. In a study by Cabral et al. [56], the elastic modulus of concrete made with 100% RCA decreased by 21%, while that of concrete made with 100% RFA decreased by 10%. For the type of concrete in which natural aggregates were replaced with recycled aggregates, the greatest loss of elastic modulus was observed for RCFAC-100, a decrease of about 17%. This is consistent with the results of studies conducted by Pedro et al. [23] and Corinaldesi and Moriconi [64], which reported reductions in modulus of 20.4% and 21%, respectively.

The addition of 10 and 20% of RP caused only 2 and 6% of elastic modulus loss, showing superior modulus compared to other types of concrete, but a sharp loss of 23% was observed at 30% RP addition. Although this was not exactly consistent with the conclusion of a study by Xiao et al. [51], that replacing up to 30% of cement by RP had a minimal negative effect on the strength of concrete, the authors of the study noted that a significant reduction was observed at the RP replacement ratio of 45%.

4. Correlation between Properties of Concrete

4.1. Relationship between Compressive Strength and Density

Figure 10 shows the correlation between compressive strength and density of concretes. A tendency to increase the compressive strength was observed as the density increased, but the coefficient of determination (R^2) for all specimens was 0.50, which does not indicate a strong correlation. In particular, considering that RPC-30 mix has a very high density of about 2300 kg/m^3 at the low strength of 26 MPa compared to other mixtures, regression analysis of concrete made with recycled aggregates (i.e., RCAC, RFAC, and RCFAC) and RP was performed separately. As a result, strong correlations were found in both groups. Concrete with RP showed a R^2 of 0.87, and concrete with aggregates had a R^2 of 0.94.

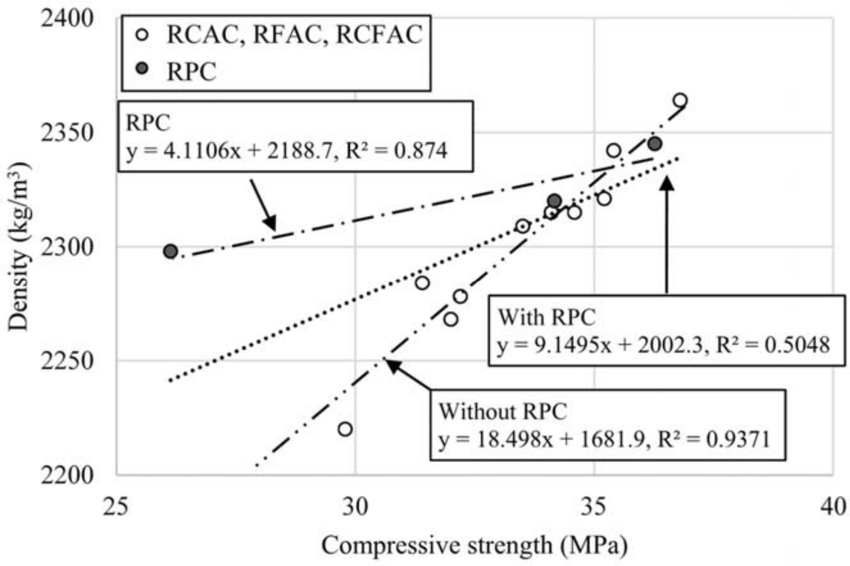

Figure 10. Correlation between compressive strength and density.

4.2. Relationship between Compressive Strength and Splitting Tensile Strength

The relationship between compressive strength (f_{cu}) and splitting tensile strength (f_{sp}) at 28 days of age is shown in Figure 11. The compressive–tensile strength relationships presented in EN 1992-1-1 [65] and ACI 318-14 [66] (Equations (1) and (2)), and prediction models proposed by other researchers [67,68] (Equations (3) and (4)), were plotted for comparison with the current results.

$$f_{sp} = 0.3 f_{cu}^{\left(\frac{2}{3}\right)} \quad (1)$$

$$f_{sp} = 0.56 f_{cu}^{0.5} \quad (2)$$

$$f_{sp} = 0.24 f_{cu}^{0.65} \quad (3)$$

$$f_{sp} = 1.49 f_{cu}^{0.32} - 1.93 \quad (4)$$

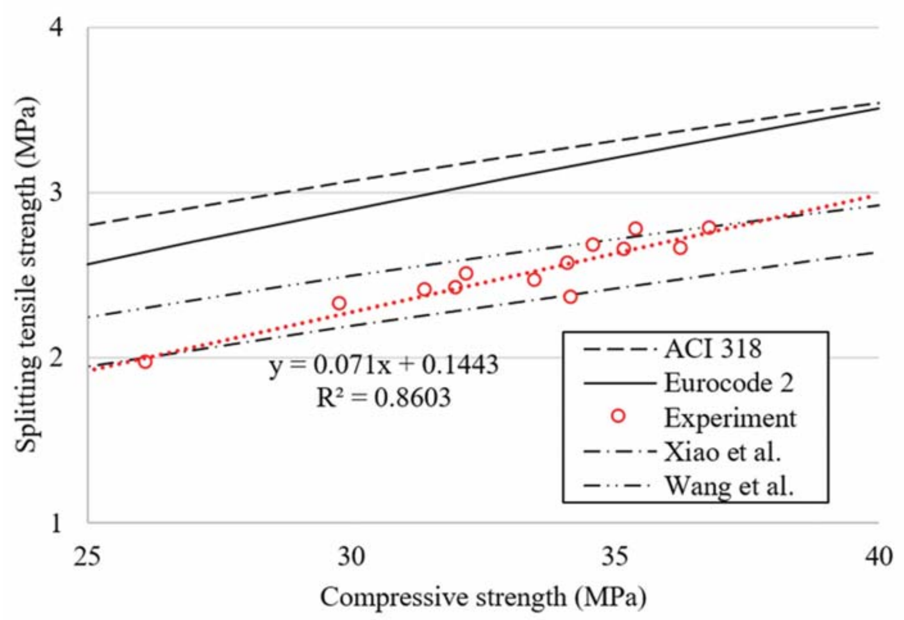

Figure 11. Correlation between compressive strength and tensile strength.

Compressive strength and splitting tensile strength in this study showed a good correlation with a R^2 of 0.86, but as can be seen in Figure 11, it is clear that the equations presented in the codes overestimated the splitting tensile strength. This may be because these two codes were not specifically developed with a focus on concrete made from recycled concrete materials. On the other hand, Equations (3) and (4) were derived based on concrete incorporating recycled aggregates, and are in good agreement with the experimental results of this study.

4.3. Relationship between Compressive Strength and Elastic Modulus

Figure 12 shows the relationship between the compressive strength and the elastic modulus (E_c) of concrete mixtures at 28 and 56 days. In Figure 12, the relationships presented in EN 1992-1-1 [65] and ACI 318-14 [66] codes (Equations (5) and (6)) and the compressive strength–modulus prediction model provided by other researchers [56,67,69] (Equations (7)–(9)) were also presented for comparison with the results of this study.

$$\mathrm{Ec} = 22(f_{cu}/10)^{0.3} \quad (5)$$

$$\mathrm{Ec} = 4700\sqrt{f_{cu}} \quad (6)$$

$$\mathrm{Ec} = 2.58 f_{cu}^{0.63} \quad (7)$$

$$\mathrm{Ec} = 4.7863 f_{cu}^{0.4485} \quad (8)$$

$$\mathrm{Ec} = \frac{10^2}{\left(2.8 + \frac{40.1}{f_{cu}}\right)} \quad (9)$$

A strong correlation with the R^2 value of 0.94 was observed between compressive strength and elastic modulus. In addition, a similar pattern of the relationship between compressive strength and splitting tensile strength found in the previous section was observed.

The equations presented in each code overestimated the elastic modulus, while the prediction models based on concrete with recycled aggregates agreed well with the current experimental results. In this regard, Wang et al. [68] pointed out that the prediction models established based on NAC may no longer be suitable because the influence of recycled aggregates on the compressive strength and on the elastic modulus is different.

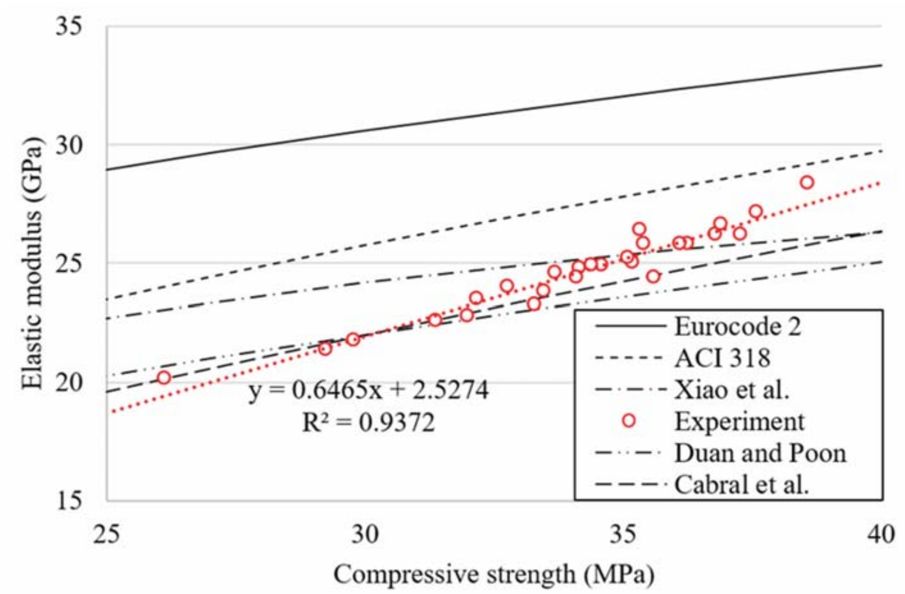

Figure 12. Correlation between compressive strength and elastic modulus.

5. Cost Analysis and Environmental Impact Assessment

In Table 7, the manufacturing cost per cubic meter of all types of concrete and the 28-day compressive strength are provided along with the cost value and eco-efficiency. The cost value was obtained by dividing the 28-day compressive strength by the manufacturing cost, while the eco-efficiency was obtained by dividing the 28-day compressive strength by the GWP index. Both values are represented as relative value based on the RC value, i.e., RC has a value of 1.

Table 7. Cost and environmental analysis of various concretes.

Mix	Cost (USD/m^3)	GWP (kg CO_2-eq./m^3)	Compressive Strength (MPa)	Cost Value	Eco-Efficiency	Target Strength
RC	56.20	405.22	36.8	1	1	Pass
RCAC-30	54.73	399.88	35.2	0.98	0.97	Pass
RCAC-60	53.20	394.47	33.5	0.96	0.93	Pass
RCAC-100	51.21	387.32	31.4	0.94	0.89	Pass
RFAC-30	55.33	401.94	35.4	0.98	0.97	Pass
RFAC-60	54.47	398.67	34.6	0.97	0.96	Pass
RFAC-100	53.31	394.31	32.2	0.92	0.90	Pass
RPC-10	52.33	378.60	36.3	1.06	1.06	Pass
RPC-20	48.45	351.87	34.2	1.08	1.07	Pass
RPC-30	44.56	325.15	26.1	0.90	0.89	Fail
RCFAC-30	53.85	396.60	34.1	0.97	0.95	Pass
RCFAC-60	51.46	387.92	32.0	0.95	0.91	Pass
RCFAC-100	48.32	376.40	29.8	0.94	0.87	Fail

All the concrete mixes incorporating recycled concrete materials are about 2.6% to 20% more economical than RC made of NCA and NFA, in proportion to the material replacement ratio. It should be noted that the concretes with the lowest manufacturing cost are RPC-30 and RCFAC-100, but these two mixtures did not achieve the target strength. Therefore, the unit price of concrete should not be considered as the only parameter in the economic analysis, and cost–benefit analysis should be performed based on the intended purpose. Since the slump of all concretes was within the tolerance range (100 ± 25 mm), a target strength of 30 MPa should be considered in this study. The same principle applies to eco-efficiency analysis. In view of that, the mixtures with values higher than RC (i.e., values greater than 1) were RPC-10 and RPC-20. Since the unit cost of OPC is more than ten times higher than that of aggregate, replacing OPC by RP even at a low replacement ratio has a higher value over replacing natural aggregates with recycled aggregates.

A similar pattern was observed in environmental impact assessments. It is clear that concrete made from recycled materials has a lower GWP than RC, providing environmental benefits. When RCA and RFA were used separately at 100%, GWP could be reduced by about 3–4%, and when both materials were used simultaneously, about 7% of GWP could be reduced. Moreover, concrete with 10% replacement of OPC with RP reduced GWP by 7%, which is similar to that of concrete incorporating 100% RCA and 100% RFA simultaneously. The environmental impact was reduced by up to 20% as the RP content was increased up to 30%. This is because the CO_2 emissions from cement manufacturing were much higher than those from aggregate manufacturing. According to Flower and Sanjayan [4], the CO_2 emission coefficient related to cement production is 0.82 t CO_2-eq./ton, while those of coarse granite aggregates and fine aggregates are 0.0459 and 0.0139 t CO_2-eq./ton, respectively. Therefore, the replacement of OPC by RP can provide greater environmental benefits than the replacement of natural aggregates by recycled aggregates. For this reason, in the eco-efficiency defined as the ratio of the 28-day compressive strength to the GWP, concretes that showed higher values than RC were RPC-10 and RPC-20, and the remaining mixtures were in the range of 0.87–0.97, showing lower values than RC.

Considering the above, the cost and environmental benefits of using recycled concrete materials are not sufficient to offset the unfavorable effect on the mechanical performance of concrete in some cases. Nevertheless, it should be noted that all concretes, except for RPC-30 and RCFAC-100, achieved their target strength and thus could be applied for structural purposes. In terms of cost value and eco-efficiency, the addition of 20% RP is recommended. In addition, although the cost value and eco-efficiency were lower than those of RC, the separate uses of 100% RCA and 100% RFA can be considered as a viable option because the unit cost and GWP of RCAC-100 and RFAC-100 were lower than those of RC while satisfying the required compressive strength. When RCA and RFA are used simultaneously, the replacement rate can be up to 60%.

6. Conclusions

A study was conducted on the properties and the economic and environmental impact of concrete incorporating recycled concrete materials of different size fractions obtained from concrete waste. The following conclusions can be drawn:

- With the increased replacement ratios of natural materials by recycled materials, the slump of the concrete mixes was reduced (up to 19%) and the air content was increased (up to 0.6%) compared to the reference concrete, but the fresh properties were within the range required by the standard.
- As the replacement ratio increased, the mechanical properties of concrete decreased. The properties decreased in the order of RFAC, RCAC, and RCFAC at the same replacement ratio.
- The reduction of compressive strength and elastic modulus was only 1–4% for concrete with 10% RP and 6–8% for concrete with 20% RP. However, when 30% RP was added, the mechanical properties showed a rapid decrease of 23~29%, thus special attention is required for its use. Nevertheless, all mixtures could be applied as structural concretes under different environmental exposure conditions.
- The relationship between compressive strength, elastic modulus, and splitting tensile strength of concrete containing different size fractions of recycled concrete materials showed a strong correlation. However, for the relationship between compressive

strength and density, RPC needs to be considered separately from RCAC, RFAC, and RCFAC.

- Replacing OPC with RP by up to 20%, cost value and eco-efficiency were superior to those of RC. Although the cost value and eco-efficiency of concrete incorporating RCA and RFA were lower, the production cost and GWP were lower than those of RC; thus, it can be considered economical and eco-friendly if the intended requirements are achieved.

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Closed-loop recycling of C&D waste: Mechanical properties of concrete with the repeatedly recycled C&D powder as partial cement replacement

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ABSTRACT

Studies have been conducted on the repeated recycling of recycled coarse aggregates and recycled fine aggregates obtained from concrete waste, but no research has been conducted on the repeated recycling of recycled powder as a partial replacement for cement, which is pointed out as a major source of CO_2 in the concrete industry. This paper investigates the closed-loop recycling potential of construction wastes by evaluating the effects of repeated use of concrete powder generated in the production of recycled aggregates on the selected fresh and hardened mechanical properties of concrete. Through a series of concrete making and crushing, once-, twice-, three times-recycled concrete powder of less than 150 µm was collected and used as a partial replacement for cement in concrete matrices at replacement levels of 10%, 20% and 30%. According to the experiment results, the replacement ratio and the number of recycling of concrete powder are parameters that affect the properties of concrete, and in particular, the replacement ratio is more affected than the number of recycling. The strength of concrete containing 10–20% concrete powder surpassed the target strength by up to 21% over three times of recycling, and the cost and environmental benefits increase in proportion to the number of concrete powder recycling. This study can contribute to the valorization of construction waste by providing a new initiative for multi-recycling of concrete powder and a closed-loop recycling system for construction waste.

1. Introduction

The construction industry is a major backbone industry in many countries (Hillebrandt, 2000), and concrete is a major material used worldwide in construction and infrastructure applications. Developed countries face the challenge of replacing aging infrastructure, while developing countries are investing heavily in new infrastructure (Monteiro et al., 2017). In this process, a massive amount of concrete is required, and cement is generally used as a binder for concrete production. CO_2 emissions from the cement industry are an international social concern that requires immediate action. The cement industry is the third largest source of anthropogenic CO_2 emissions and is also responsible for carbon monoxide and other heavy metals (IEA, 2018; Lei et al., 2011). Reducing dependence on cement is linked to the sustainability challenges in this industry (Xiao et al., 2018). However, despite these negative environmental impacts, the consumption of cement is expected to continue to increase in line with population growth, infrastructure development and economic growth in developing countries (IEA, 2020). Therefore, in order to ensure the future competitiveness of concrete as a construction material, consumption of natural resources and environmental impact must be reduced (Proske et al., 2013).

Construction activities are a major source of waste in many countries. The waste is generated not only from the demolition of structures but also from new construction, and can also be generated by disasters such as earthquakes. Construction and demolition (C&D) waste accounts for about 36% of the total waste generated in the European Union (Eurostat, 2021). Akhtar and Sarmah (2018) reported that construction waste generated by 40 countries in 2012 amounted to about 3 billion tonnes. Recycling of C&D waste is, on the one hand, an unavoidable challenge, and on the other hand, an opportunity to solve problems such as land occupancy due to landfilling, consumption of natural resources, and water and air pollution from illegal dumping and quarrying. Therefore, recycling of C&D waste is encouraged or mandated by several government agencies (Kim, 2021a; Tam et al., 2018).

Through recycling process concrete waste is classified into recycled coarse aggregate (RCA), recycled fine aggregate (RFA) and recycled powder (RP), and various and comprehensive studies have been conducted on its properties and uses. In particular, as a raw material that

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occupies the largest proportion in concrete, RCA has attracted the attention of researchers. In general, when RCA is incorporated into concrete, the durability and mechanical properties of concrete deteriorate (Kim, 2021b; Kim et al., 2016). This trend is also observed when using RFA and RP. According to some literature (Andreu and Miren, 2014; López-Gayarre et al., 2009), the use of high quality RCA can mitigate the loss of properties of recycled aggregate concrete (RAC). Several technologies have been proposed to produce high-quality RCA, but these technologies improve the aggregate quality at the cost of increasing manufacturing costs and energy consumption. It is also necessary to consider RFA and RP generated as by-products in the concrete recycling process (Evangelista and de Brito, 2014; Rodrigues et al., 2013). In the study carried out by Nagataki et al. (2004), the proportions of RCA and RFA produced from 1 ton of concrete using a crusher were 60% and 40%, and the proportion of RFA increased to 65% with additional crushing. Therefore, in order to maximize the utilization of recyclable C&D wastes, it is necessary to investigate and discuss the use of the generated RFA and RP.

As mentioned above, the effect of RP on concrete properties is similar to when RCA and RFA are used: as the replacement rate of RP for cement increases, the workability, strength, and durability of cement composites tend to decrease (Tang et al., 2020). However, in the study of Ma et al. (2021), the loss of compressive strength compared to control concrete at a RP replacement of 10% was only 0.4–3.4%. Xiao et al. (2018) reported strength losses of 2.5% and 7.7%, respectively, at replacement levels of 15% and 30%. In contrast, in some literature (Moon et al., 2005; Xue et al., 2016), a slight improvement in properties is observed in concrete with RP. Kim (2017) mentioned that concrete powder can be used for concrete manufacturing since it achieved the target strength at 15% replacement of RP, and some literature recommends the use of RP within 30% (Kwon et al., 2015; Tang et al., 2020). However, unlike RCA and RFA, there has been no study on the effect of repeated recycling of RP as a cement substitute on concrete properties. In general, concrete that is recycled several times deteriorates as the number of times increases. This is because the quality of the RCA lowers as the number of recycling increases, which contributes to the degradation of the performance of the repeatedly-recycled RAC (Thomas et al., 2018, 2020). Therefore, it may be desirable to repeatedly recycle RP as a cement substitute in terms of the feasibility of closed-loop recycling of concrete waste.

In summary, the study of the repeated recycling of RP as a cement substitute is justified and desirable for the following reasons: (i) in a long-term perspective, concrete should be able to be recycled multiple times; (ii) RP generation increases with the number of concrete recycling; (iii) studies on the repeated recycling of RP have not been conducted to date. Therefore, repeated recycling of RP is a crucial point towards minimizing construction waste. The main scientific question to be addressed in this study is as follows: "How can we achieve closed-loop recycling of construction waste and contribute to the sustainability of the concrete industry by utilizing recycled powder that is constantly generated during the concrete recycling process?".

The concept of closed-loop recycling referred to in this study is illustrated in Fig. 1. The generated C&D waste goes through a recycling process to turn the waste into RCA, RFA and RP, which acts as a substitute for natural aggregate (NA) and cement in concrete. This recycled concrete is later crushed and recycled repeatedly as RCA, RFA and RP, which is used as the main raw material for recycled concrete. By repeating this process, concrete waste can be completely recycled without landfilling. Therefore, in this study, concrete properties are investigated when concrete powder, which is produced as a by-product in the process of crushing concrete waste to obtain RCA and RFA, is used as a substitute for cement. The properties of concrete include slump, air content in the fresh state, and compressive strength, splitting tensile strength and elastic modulus in the hardened state. Based on the experimental results, an environmental impact and cost analysis is performed.

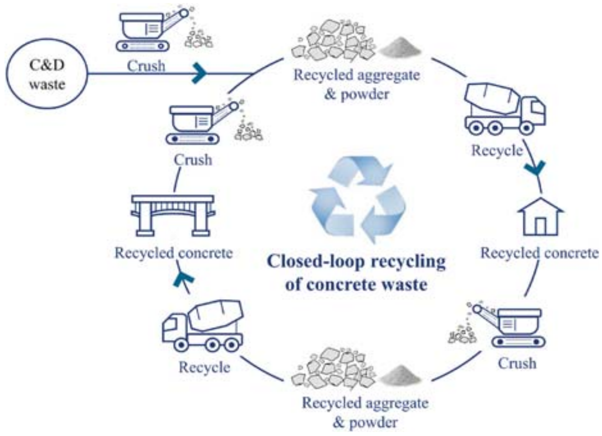

Fig. 1. Closed-loop recycling of construction and demolition waste for concrete.

This study emphasizes the new concept of recycling of RP generated during the concrete recycling process. Consequently, the repeated recycling of RP can contribute to the minimization and valorization of construction waste, as well as providing an initiative for the closed-loop recycling of construction waste and sustainable development.

2. Experimental program

2.1. Materials

The cement used throughout the experimental program was ordinary Portland cement with a density of 3.14 g/cm^3 and Blaine specific surface area of 3550 cm^2/g.

Natural granitic crushed aggregate with a maximum nominal size of 25 mm and siliceous river sand were used as natural coarse aggregate (NCA) and natural fine aggregate (NFA).

2.2. Recycled concrete aggregate and powder production

The main object of this study is to determine the potential of repeatedly recycled RP as a cement substitute. A series of concrete casting and crushing works were preceded to obtain RP that was recycled a total of three times. The experimental flow for the production of repeatedly recycled RP is shown in Fig. 2: Natural aggregate concrete (NAC) was made from the raw materials mentioned in section 2.1 and the properties of the concrete were evaluated. The NAC specimens tested at 7 and 28 days were collected in containers, and when 56-day mechanical strength test was completed, the specimens were primarily crushed with a universal testing machine and then secondarily crushed in the Los Angeles ball mill. The crushed specimens were classified by size into RCA1 (4.75–25 mm), RFA1 (150 μm-4.75 mm), and RP1 (0–150 μm). The first-generation RAC (RAC1) was then made of 100% RCA1 and 100% RFA1 as replacements of NCA and NFA, and the first-generation RPC (RPC1) was cast using RP1 as a cement substitute at replacement ratios of 10%, 20% and 30%, respectively. After testing the properties, RAC1 was crushed in the above-mentioned manner to obtain RCA2, RFA2 and RP2, which were used for the production of the second-generation recycled concrete, RAC2 and RPC2, respectively. Repeatedly, RAC2 was crushed to obtain RCA3, RFA3 and RP3, which were used for the third-generation recycled concrete, RAC3 and RPC3.

Table 1 shows the mix proportions of parent concretes based on ACI mix design (ACI 211.1-91, 1991) to obtain a total of three generations of RP as above-described in this section. The target slump of NAC was set at 100 mm, and the target compressive strength at 28 days was set at 30

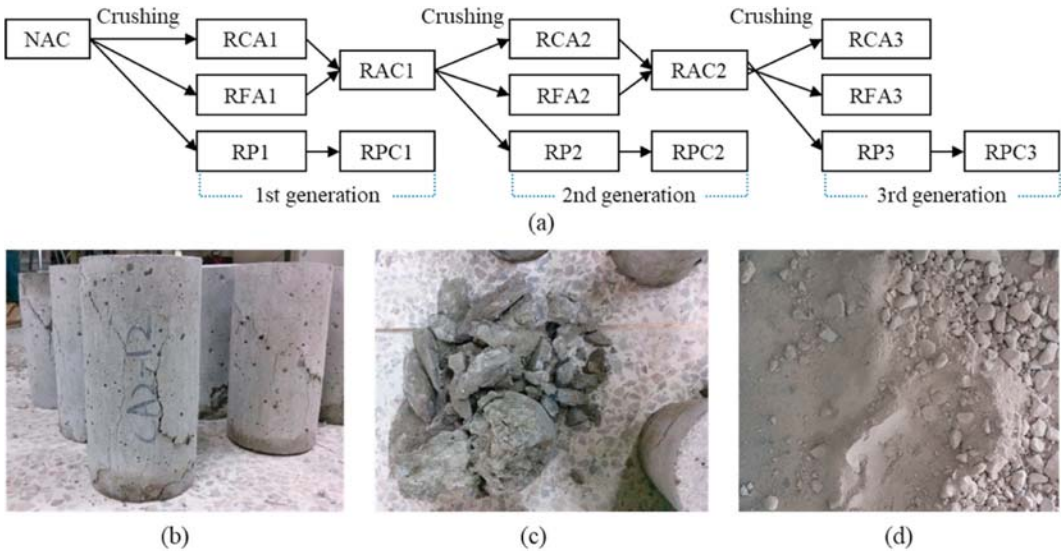

Fig. 2. Experimental flow for the production of repeatedly recycled powder concrete: (a) experimental flow; (b) concrete specimens tested; (c) concrete specimens crushed by a universal testing machine; (d) concrete specimens after ball milling.

Table 1
Mix proportions of parent concretes and physical properties of aggregates obtained therefrom.

ID	w/c	Water, kg/m^3	Cement, kg/m^3	NFA, kg/m^3	RFA1, kg/m^3	RFA2, kg/m^3	NCA, kg/m^3	RCA1, kg/m^3	RCA2, kg/m^3
NAC	0.45	175	389	740	0	0	1011	0	0
RAC1	0.45	175	389	0	632	0	0	909	0
RAC2	0.45	175	389	0	0	563	0	0	856
Specific gravity				2.60	2.22	1.98	2.68	2.41	2.27
Water absorption, %				0.91	5.38	7.91	0.88	4.45	6.44

MPa. Table 1 also shows the physical properties of aggregates used in the study: NCA; NFA; RCA1 and RFA1 acquired from NAC; RCA2 and RFA2 obtained from RAC1. For both RCA and RFA, water absorption was increased but specific gravity was decreased with the number of recycling, which is attributed to the adhered mortar remaining on the surface of the original aggregate after concrete crushing. The specific gravity and water absorption of aggregate are interrelated properties that are greatly affected by the adhered mortar content, and the adhered mortar content is proportional to the water absorption and inversely proportional to the specific gravity of aggregate (Salesa et al., 2017; Zhu et al., 2016).

For mixing, NCA, NFA and RFA in saturated surface dry (SSD) state were used. On the other hand, RCA in the SSD state contributes to the loss of mechanical strength of RAC (Poon et al., 2004), thus, RCA saturated was dried in the air 24 h before mixing to retain moisture but not fully saturated and stored in a temperature- and humidity-controlled room (i.e. 20 °C and relative humidity of 60%) (Jang et al., 2021).

All concrete mixtures were prepared in a pan mixer with a capacity of 60 L. While the mixer was running, coarse and fine aggregates were placed in the mixer and mixed for 30 s, then cement was added and mixed for 90 s. After that, water was added and further mixed for 120 s to obtain a homogeneous concrete mixture.

2.3. *Mix design*

The mix proportions for concrete mixtures containing RP with different recycling generations are given in Table 2. NAC is a control mixture made from natural raw materials. RPC stands for concrete mixtures containing RP. Each generation of RPs was used at 10%, 20% and 30% replacement by weight for cement. All other materials were

Table 2
Mix proportions of natural aggregate concrete and three generations of recycled powder concrete.

ID	w/c	Water, kg/m^3	Cement, kg/m^3	NFA, kg/m^3	NCA, kg/m^3	RP1, kg/m^3	RP2, kg/m^3	RP3, kg/m^3
NAC	0.45	175	389	740	1011	0	0	0
RPC1-10%	0.45	175	350	740	1011	39	0	0
RPC1-20%	0.45	175	311	740	1011	78	0	0
RPC1-30%	0.45	175	272	740	1011	117	0	0
RPC2-10%	0.45	175	350	740	1011	0	39	0
RPC2-20%	0.45	175	311	740	1011	0	78	0
RPC2-30%	0.45	175	272	740	1011	0	117	0
RPC3-10%	0.45	175	350	740	1011	0	0	39
RPC3-20%	0.45	175	311	740	1011	0	0	78
RPC3-30%	0.45	175	272	740	1011	0	0	117

kept constant to reflect only the influence of RP by recycling generations. The code for each mixture denotes the 'recycling generation-replacement ratio'. For example, RPC1-10% represents concrete mixed with 10% of first-generation RP as a substitute for cement, and RPC3-30% connotes concrete mixed with 30% of third-generation RP.

2.4. Test methods

As previous studies on repeated recycling of RP are very scarce, standardized tests that can represent the most basic quality/properties of concrete have been conducted. For fresh properties, slump (ASTM C143/C143M-20, 2020) and air content (ASTM C231/C231M-17a, 2017) were recorded, and for hardened properties, compressive strength (ASTM C39/C39M-21, 2021), splitting tensile strength (ASTM C496/C496M-17, 2017), and elastic modulus (ASTM C469/C469M-14e1, 2014) were included. Compressive strength and elastic modulus were measured at 7, 28, and 56 days, and splitting tensile strength was performed at 28 days. Standard cylinder molds with dimensions of 100 mm × 200 mm were used for specimen preparation. The specimens were cured in water until the testing day and a minimum of three specimens was used for each test and age according to ASTM C192 (ASTM C192/C192M-19, 2019).

To verify the environmental and economic benefits of multi-recycled RPC, the environmental impact and manufacturing cost of the concrete used in this study was analyzed. For environmental impact, global warming potential (GWP), acidification potential (AP), and fossil fuel depletion potential (FP) indices were evaluated based on the equation presented by Khodabakhshian et al. (2018). The cost analysis was conducted based on the prices of raw materials (as of November 2021) surveyed by the Construction Association of Korea.

3. Results and discussion

3.1. Properties of concrete with repeatedly recycled coarse and fine aggregate

The fresh and hardened properties of NAC, RAC1 and RAC2 produced to obtain a total of three generations of RP are shown in Table 3.

The slump of RACs was lower than that of NAC, and in particular, it showed a tendency to decrease when the number of recycling increases. In comparison with NAC, the slump of RAC1 and RAC2 was reduced by 14% and 20%, respectively, even though the aggregate was pre-wetted. This is associated with the increasing adhered mortar content of RCA and RFA as the number of recycling increases. The adhered mortar increases the water absorption of the aggregate and absorbs mixing water during the concrete mixing process, contributing to lowering the workability of the mixture. Nevertheless, the slump of all concrete mixtures was within a tolerance of ±25 mm according to ASTM C94 (ASTM C94/C94M-21b, 2021).

As the number of recycling increased, the air content of RPC showed an upward trend. Compared with NAC, the air content of RAC1 and RAC2 increased by 0.6% and 1.0%, respectively. This is because the increased adhered mortar content resulting from the repeated recycling of RCA contributes to an increase in the porosity of concrete (Thomas et al., 2019). This finding is consistent with the results of the literature (Huda and Alam, 2014). Nonetheless, the air content of RACs recycled twice in total satisfied the tolerance of 4.5 ± 1.5% for concrete with a nominal size of 25 mm exposed to the freeze-thaw cycle in accordance with the ASTM C94 (ASTM C94/C94M-21b, 2021).

Table 3
Fresh and hardened properties of natural and recycled aggregate concretes.

ID	Slump, mm	Air content, %	Hardened density (d-28), kg/m^3	Compressive strength (d-28), MPa	Elastic modulus (d-28), GPa
NAC	105	3.8	2364	36.8	26.2
RAC1	90	4.4	2220	29.8	21.8
RAC2	80	4.8	2160	24.4	18.4

For the hardened properties, repeated recycling reduces density, strength and elastic modulus of the corresponding RAC. The 28-day hardened densities of RAC1 and RAC2 were 6% and 9% lower than that of NAC. The 28-day compressive strength was dropped by 19% for RAC1 and 34% for RAC2 and the both RACs did not achieve the target compressive strength of 30 MPa. The loss of elastic modulus was found to be 21% and 35% at each recycling generation. These results are consistent with previous studies on repeatedly recycled RAC (Abreu et al., 2018; Huda and Alam, 2014; Thomas et al., 2020). The downward trend in the properties is a result of downgrade of RCA quality due to the repeated recycling. Micropores and microcracks formed in RCA due to multiple crushing and the relatively weaker interfacial transition zone in RAC are factors contributing to the decrease in the mechanical properties of RAC which recycled several times (Zhu et al., 2019b).

3.2. Fresh properties of concrete with repeatedly recycled concrete powder

To evaluate the effect of RP recycled a total of three times as a partial cement replacement on the fresh properties of concrete, all mixtures were tested for slump and air content, and the results are shown in Fig. 3. The slump and air content of NAC are also shown in Fig. 3 for comparison.

Similar to the case of the parent concretes incorporating RCA and RFA, the RP decreases its slump with the replacement ratio. For the first-generation RPC (i.e. RPC1), RPC with 10% RP replacement (RPC1-10%) showed the same slump as NAC (105 mm), but it reduced by 10% and 19% at 20% (RPC1-20%) and 30% (RPC1-30%) replacement ratios, respectively. A similar trend was observed for second- and third-generation RPCs. At the RP replacement ratios of 10%, 20% and 30%, the slump of the RPC2 series was reduced by 5%, 14%, and 19% than that of the NAC. For the third-generation RPC, slump losses of 5%, 14%, and 24% were observed, respectively. The decrease in workability of RPC with increasing RP replacement ratio can be attributed to the relatively high absorption and irregular microstructure of RP (Kim and Choi, 2012). This result is consistent with previous studies (Cantero et al., 2020; Xiao et al., 2018). As shown in Fig. 3, the slump loss slightly increases with the number of recycling, but at the same replacement level, its influence of the loss is relatively insignificant. From first-to third-generation, the slump of RPC-10% ranges from 100 mm to 105 mm, that of RPC-20% is in the range of 90–95 mm, and RPC-30% had the slump of 80–85 mm. The concretes incorporating 10% and 20% of RP which recycled twice and three times (RPC2-10%, RPC2-20%, RPC3-10% and RPC3-20%) show a higher slump than concrete with 30% of RP recycled once (RPC1-30%). Therefore, the workability of RPC seems to be more affected by the replacement ratio than by the number of recycling.

The air content of all mixtures is shown in Fig. 3. The repeated recycling of RP increases the air content of RPC, but it is within the standard range of 4.5 ± 1.5% (ASTM C94/C94M-21b, 2021).

3.3. Hardened properties of concrete with repeatedly recycled concrete powder

The test results for the mechanical properties of RPCs recycled for three generations are shown in Fig. 4.

3.3.1. Compressive strength

The 7-, 28- and 56-day compressive strengths of the concrete mixtures blended with the RPs recycled once, twice and three times as a partial replacement of cement are shown in Fig. 4 (a). The compressive strength of NAC at each age is also plotted in Fig. 4 (a).

A decrease in compressive strength is clearly observed as the replacement ratio of RP increases. Except for the control mixture, the

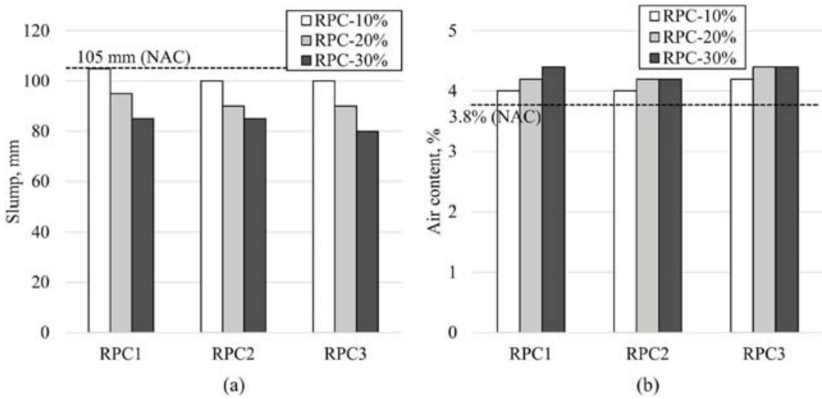

Fig. 3. Test result of mechanical properties of recycled powder concretes: (a) slump; (b) air content.

highest compressive strength at each age was found in the RPC1-10% series. The compressive strength of RPC1-10% at 7, 28, and 56 days was in the range of 29.7–37.6 MPa, but at 20% and 30% RP replacement ratios, the compressive strength tended to decline to 27.8–35.3 MPa and 21.2–29.3 MPa, respectively. The RPC-10% and RPC-20% series achieved 28-day target strength of 30 MPa for a total of 3 repeated recycling, whereas, for RPC-30%, a strength loss of up to 31% was observed depending upon the recycling cycle, and RPC-30% did not reach their target strength even at 56 days. Regarding the strength degradation of RPC, it has been reported that the reactivity of RP, which is generally lower than that of Portland cement, forms fewer hydration products and unfavorably affects the strength (Duan et al., 2020; Ma et al., 2021).

The loss of compressive strength gradually increases with the number of recycling of RP. Fig. 4 (b) shows the relative compressive strength of all concrete mixtures used in this study as a function of the recycling cycle. The relative compressive strength of the parent concrete (NAC, RAC1 and RAC2 with 100% RCA and 100% RFA) produced to obtain a total of three generations of RP, including concrete produced with RCA (Huda and Alam, 2014) and RFA (Zhu et al., 2019a) reported by other researchers, was also indicated. During a total of three recycling cycles, the compressive strength of RPC-10% is only 1–7% lower than that of NAC. At 20% replacement rate, the compressive strengths of RPC1, RPC2 and RPC3 were reduced by 7%, 11% and 14%. As shown in Fig. 4 (b), regardless of the number of recycling, the extent of this strength reduction of RPC-10% and RPC-20% is not as great as the loss of concretes with repeatedly recycled RCA, RFA, or both. At 30% replacement ratio, RPC1 recorded a relative compressive strength loss of 29%, but no decreasing trend was observed with the number of recycling. The relative strength losses of RPC2-30% and RPC3-30% were 29% and 28%, respectively. However, the replacement of 30% RP induced a greater drop in relative compressive strength in the first recycling generation than concretes with RCA, RFA or a combination of the two.

3.3.2. Splitting tensile strength

The splitting tensile strength was measured on standard cylindrical concrete specimens of 100 mm diameter and 200 mm height. The test results of splitting tensile strength at 28 days are shown in Fig. 4 (c). The results show a similar trend as the compressive strength. That is, the RPCs showed lower splitting tensile strength than the control concrete. The highest splitting tensile strength in each recycling generation was observed in concrete mixed with 10% RP (RPC1-10%, RPC2-10% and RPC3-10%). From the first-to the third-generation recycling, the 28-day splitting tensile strength of RPC with 10% replacement ratio was in range of 2.51–2.66 MPa, while RPCs with 20% and 30% replacement ratios had the strength of 2.28–2.36 MPa and 1.75–1.99 MPa, respectively. Exceptionally, the splitting tensile strength of RPC2-30% was slightly higher than that of RPC1-30% by about 1%, but it does not seem significant.

Fig. 4 (d) shows the 28-day relative splitting tensile strength of the concrete mixtures used in this study as a function of the number of recycling. The relative strengths of concrete made with 100% RCA (Huda and Alam, 2014) and concrete made with 100% RCA and 100% RFA are also indicated. There is general agreement that cement mixtures containing RCA and RP have lower strength than cement mixtures made of only natural materials (Sun et al., 2020). However, according to the study carried out by Huda and Alam (2014), the splitting tensile strength of the first- and second-generations of RAC with RCA increased by about 3–4% compared to the control concrete although it showed a sharp drop at the third-generation. Although these results have often been reported that the more angular shape of RCA contributes to improved adhesion between RCA and fresh mortar (Etxeberria et al., 2007; Sagoe-Crentsil et al., 2001), no such trend was observed in this study. For a total of three recycles, RPC1-10%, RPC2-10% and RPC3-10% had 4%, 9% and 10% lower tensile strength than the control mixture. The reduction in tensile strength for each recycling cycle of RPC-20% was 15%, 16%, and 18%. For RPC-30%, the losses were 29%, 28% and 37% respectively.

3.3.3. Elastic modulus

The elastic modulus at 7, 28 and 56 days of the RPC mixture recycled three times is shown in Fig. 4 (e). The modulus of the control mixture, NAC, is also presented. All RPC mixes exhibit a lower modulus than the control mixture, and the replacement ratio and number of recycling are parameters that decrease the modulus. At 7, 28, and 56 days, the elastic modulus of RPC1-10% was in the range of 21.3–27.2 GPa, and those of RPC1-20% and RPC1-30% were in the range of 20.1–26.4 GPa and 18.5–21.3 GPa, respectively, showing a clear decreasing trend. A similar pattern is observed for RPC2 and RPC3.

Fig. 4 (f) shows the relative elastic modulus at 28 days as a function of the recycling cycle for all concrete mixtures used in this study, including parent concretes (NAC, RAC1 and RAC2) used to obtain repeatedly recycled RP. It also shows the variation of elastic modulus of RAC with 100% RCA with the number of recycling published in a previous study (Huda and Alam, 2014). The concrete with the addition of 10% of RP as a cement substitute exhibited a better elastic modulus than that of RAC made with RCA, and the loss of modulus was only 2–4% compared to that of NAC during a total of three recycling, whereas at the replacement of 20%, the elastic modulus of RPC1, RPC2 and RPC3 decreased by 6%, 7%, and 16%, In addition, the 30% replacement showed a loss of 23% in the first recycling, resulting in a greater loss of modulus than concrete made with 100% of RCA and RFA.

3.4. Environmental and cost assessment

Environmental impact and cost assessment were performed to eval-

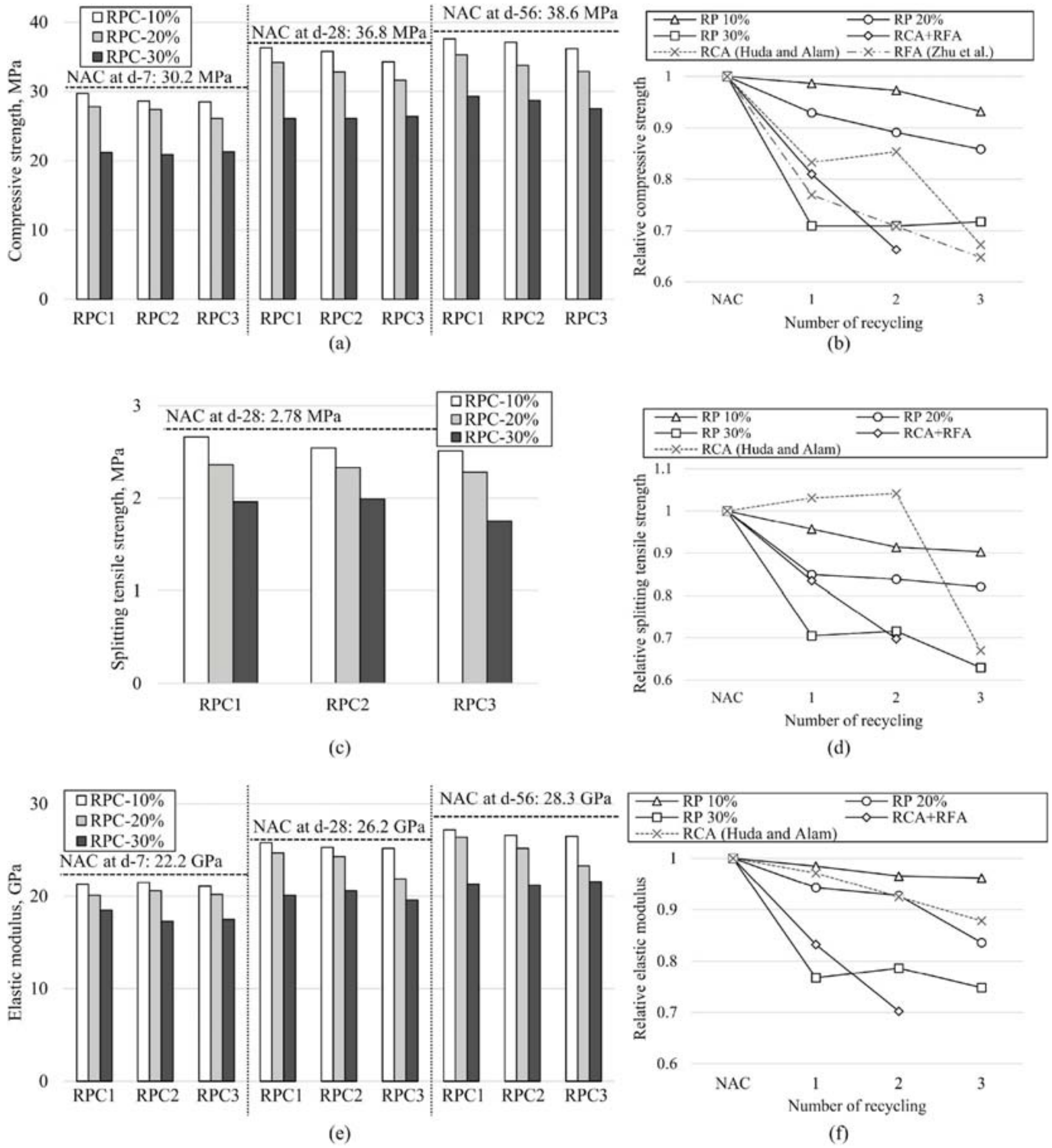

Fig. 4. Test result of mechanical properties of recycled powder concretes: (a) compressive strength at 7, 28 and 56 days; (b) relative compressive strength at 28 days; (c) splitting tensile strength at 28 days; (d) relative splitting tensile strength at day 28; (e) elastic modulus at 7, 28 and 56 days; (f) relative elastic modulus at 28 days.

uate the influence of replacing cement with RP. The global warming potential (GWP), acidification potential (AP), and fossil fuel depletion potential (FP) indices were evaluated for each mixture. The formulae (Eqs. (1-3)) for calculating the indices have been taken from a previous study (Khodabakhshian et al., 2018).

$$GWP = (0.885 \times C) + (0.0032 \times A) + (0.0025 \times W) + (1.11 \times SP) \quad (1)$$

$$AP = (0.0053 \times C) + (0.00002 \times A) + (0.0045 \times W) + (0.00481 \times SP) \quad (2)$$

$$FP = (1.49 \times C) + (0.0063 \times A) + (0.01 \times W) + (83.97 \times SP) \quad (3)$$

where C is cement content of concrete (kg/m^3); A is the aggregate content (kg/m^3); W is the water content (kg/m^3); SP is the superplasticizer content (kg/m^3).

Table 4 shows the relative environmental impact for each concrete mixture. Each effect was calculated assuming that the concrete was used a total of four times. For example, in the case of NAC, the index was calculated based on the accumulated amount of raw materials when 4 NAC productions were performed, and in the case of RPC1, the index was calculated based on the total amount of concrete in 3 NAC productions and 1 RAC production. For RPC3, the index was calculated based on the total amount of materials that NAC was used once and RAC was recycled three times. When NCA and NFA are replaced with 100% RCA and 100% RFA, the reduction in GWP, AP, and FP is negligible with less than 0.01%. The indices of GWP, AP, and FP of the first-generation RPC decreased from 2% to 7%, from 2% to 5%, and from 2% to 5%. In the second-generation RPC, the indices are reduced by 5–15%, 4–11%, and 3–9%. The third-generation RPC reduced them by 7–22%, 5–16%, 5–14%. This clearly shows that among the concrete ingredients, cement has the greatest environmental impact. The environmental benefits of

Table 4
Environmental and cost assessment.

ID	Environmental analysis			Cost analysis			Target strength
	GWP	AP	FP	Fck, MPa	Cost, KRW	Value (Fck/ Cost)	
NAC	1.00	1.00	1.00	147.2	204211	1.00	Pass
RAC1	1.00	1.00	1.00	140.2	194691	1.00	Fail
RAC2	1.00	1.00	1.00	127.8	193890	0.91	Fail
RPC1-10%	0.98	0.98	0.98	146.7	201138	1.01	Pass
RPC1-20%	0.95	0.96	0.97	144.6	198065	1.01	Pass
RPC1-30%	0.93	0.95	0.95	136.5	194991	0.97	Fail
RPC2-10%	0.95	0.96	0.97	145.7	198065	1.02	Pass
RPC2-20%	0.90	0.93	0.94	140.6	191918	1.02	Pass
RPC2-30%	0.85	0.89	0.91	125.8	185772	0.94	Fail
RPC3-10%	0.93	0.95	0.95	143.2	194991	1.02	Pass
RPC3-20%	0.85	0.89	0.91	135.4	185772	1.01	Pass
RPC3-30%	0.78	0.84	0.86	115.4	176552	0.91	Fail

RP as a replacement for cement increase as recycling cycles increase.

The cost of each raw material was selected based on prices information in Korea: cement, 78800 KRW/ton; NCA, 10450 KRW/ton; NFA, 11540 KRW/ton; RCA, 5000 KRW/ton; RFA, 8000 KRW/ton; Water, 7400 KRW/ton. Since RP was considered a by-product or waste generated from C&D waste, there was no information on the price. The cost was calculated based on the cumulative amount of material used for a total of four times. Compressive strength is also shown for value evaluation. The value means the 28-day compressive strength (f_{ck}) divided by the production cost, and the relative values of each mixture are shown Table 4. Like environmental analysis, NAC quadruples the amount of raw material used to manufacture a cubic meter and the 28-day compressive strength obtained, whereas RPC3-30% accumulates the compressive strength and cost of NAC, RPC1-30% and RPC2-30%. As shown in Table 4, concretes made by recycled materials (RCA, RFA and RP) are less expensive than NAC, but also has lower compressive strength, thus, some mixtures do not contain a higher value. Under the condition of achieving the target strength of 30 MPa and positive value higher than 1.00, the use of RP within 20% of the total three recycling times is desirable. However, since the formulae adopted to evaluate the environmental impact in this study was based on the concrete mix proportion, there is a limit to accurately evaluating the environmental benefits of repeated recycling. Further studies on the detailed life cycle assessment of repeatedly recycled RP should be conducted taking various factors into account.

4. Discussions

In this study, the mechanical properties of RAC and RPC from various recycling generations and replacement ratios were investigated, and the test results confirmed that both are parameters affecting the fresh and hardened mechanical properties of RAC and RPC. Under the conditions set in this study (10–30% replacement ratios; three times of recycling), all properties investigated were found to be more affected by the replacement ratio rather than the number of recycling. As an example, concrete containing 10% RP recycled three times (RPC3-10%) showed better properties than concrete containing 20% RP recycled once (RPC1-20%). In both RAC and RPC, degradation of properties is observed with the number of recycling, but the factors that cause this degradation are different. The deterioration in workability, density, strength and elastic modulus of concrete made with RCA and RFA is mainly due to the poor quality of the aggregates used. The physical properties of NCA change to RCA with low density and high water absorption as the amount of attached mortar increases with the number of recycling. Whereas, for concrete with RP, the decrease in properties is attributed to the low chemical reactivity of the inert RP rather than the physical properties of RP (Wu et al., 2021). The low reactivity of RP leads to the formation of fewer hydration products and does not contribute to strength development. However, as shown in the results, the addition of 10% RP achieved about 95% performance compared to NAC in compressive strength and elastic modulus during a total of three recycling, showing that the loss of properties was less than when RCA and RFA were repeatedly recycled. Although all RPC mixtures exhibited lower properties than NAC, the purpose of investigating the properties of RPC is to find the optimal way to use RP as a concrete material. With this in mind, if evaluated based on the target compressive strength, it was possible to achieve the target strength even with the addition of 20% of RP recycled three times (RPC3-20%). Furthermore, the use of RP as an alternative to Portland cement has environmental benefits such as reducing CO_2 emissions, conserving natural resources, and saving landfill space. Thus, the results investigated in this study can suggest a sustainable use of RP generated in the form of by-products from the concrete recycling process, and further contribute to the establishment of a closed-loop system for construction waste.

5. Conclusions

This study presents an initiative for closed-loop recycling of construction and demolition waste through repeated recycling of concrete powder, a by-product generated in the production of recycled aggregates. Over three times of recycling, selected properties of concretes incorporating RP were evaluated at replacement ratios of 10%, 20%, and 30%. The general conclusion derived from this study is that the repeated recycled concrete powder has potential benefits as an alternative to Portland cement in terms of mechanical properties, environmental impact and cost. Consequently, RP generated during the recycling process of concrete waste can be recycled multiple times without significant loss of properties, unlike RCA and RFA. The potential for multiple recycling of concrete waste observed in this study can give momentum to the efforts towards a circular economy of the concrete industry. In particular, through continuous and effective recycling of concrete powder, it is expected to contribute to waste valorization and resolving environmental issues such as resource depletion, CO_2 emission, and waste generation.

More relevant studies need to be performed for systematic substantiation regarding the effects of repeated recycling of RP. The RP used in this study was obtained from single-source concrete waste, and the experiments were conducted at the laboratory level. Therefore, for generalization, further studies should take into account the variability of the qualities of construction waste powder. In addition, further studies on the microstructural analysis and durability of repeatedly-recycled RP are recommended.

CRediT authorship contribution statement

Jeonghyun Kim: Conceptualization, Methodology, Data curation, Formal analysis, Validation, Visualization, Writing – original draft. **Haneol Jang:** Resources, Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Statement of co-authorship

In this chapter, the contributions of the author over the multi-authored publications [A3]-[A5] composing this doctoral dissertation are declared. Furthermore, the contribution of each co-author can be found in the 'CRediT authorship contribution statement' stated in each publication.

- [A3] Influence of mix design on physical, mechanical and durability properties of multi-recycled aggregate concrete. Materials, 16(7), 2744. DOI: 10.3390/ma16072744
  The author's own contributions: conceptualization, methodology, validation, formal analysis, investigation, data curation, visualization, writing—original draft preparation

- [A4] An experimental study on structural concrete containing recycled aggregates and powder from construction and demolition waste. DOI: 10.3390/ma15072458
  The author's own contributions: conceptualization, methodology, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing

- [A5] Closed-loop recycling of C&D waste: Mechanical properties of concrete with the repeatedly recycled C&D powder as partial cement replacement. Journal of Cleaner Production, 343, 130977. DOI: 10.1016/j.jclepro.2022.130977
  The author's own contributions: conceptualization, methodology, data curation, formal analysis, validation, visualization, writing – original draft.