*recycling*

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# Assessment of the Applicability of Waste Concrete Fine Powder as a Raw Material for Cement Clinker

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**Abstract:** The cement industry is responsible for a significant portion of global $CO_2$ emissions, primarily due to the decarbonatization of limestone during clinker production. To mitigate this environmental impact, this study investigated the feasibility of using waste concrete fine powder, produced during the recycling of waste concrete, as a decarbonized raw material in cement clinker production. As a decarbonized material, waste concrete fine powder presents a valuable opportunity to reduce $CO_2$ emissions typically produced during the decarbonatization of limestone in clinker production. In addition, its use supports the recycling of construction waste, contributing to both emissions reduction and resource sustainability. In this study, samples were collected from 20 intermediate treatment plants in South Korea, where the chemical composition, particle size distribution, and carbonation rate of the fine powders were analyzed. The experimental results show that the properties of waste concrete fine powder vary significantly depending on the recycling process. Road construction aggregate production plants, which typically involve two to three crushing stages, produce fine powders with higher CaO content (28–31%) and consistent particle size distributions. In contrast, plants producing aggregates for concrete, which involve four to six crushing stages, produce powders with lower CaO content (around 20%) and greater variability in particle size. The average carbonation rate of 7.44% suggests that these fine powders can replace limestone in clinker production. It is estimated that substituting 5% of limestone with waste concrete fine powder could reduce $CO_2$ emissions from limestone decarbonatization by approximately 952,560 tons in 2023, representing a 3.34% decrease in total emissions from clinker production. However, it is important to note that the $CO_2$ emissions reduction calculation is not from a lifecycle perspective, without considering the energy-related emissions from recycling waste concrete fine powder. Nevertheless, this study highlights the potential for waste concrete fine powder to serve as a sustainable raw material for the cement industry, contributing to both $CO_2$ reduction and efficient recycling of construction waste.

**Keywords:** cement clinker production; waste concrete fines; $CO_2$ emissions reduction; recycled aggregate; carbonation rate



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## 1. Introduction

In South Korea, the cement industry is a representative high-greenhouse gas (GHG)-emitting industry, releasing approximately 39 million tons of GHGs annually as of 2019 [1–3]. Limestone, which accounts for approximately 90% of the raw materials used to produce clinker—the semi-finished product of cement—is a major source of $CO_2$ emissions in cement manufacturing. Because limestone is composed of calcium carbonate, containing about 44% $CO_2$ by weight, it releases $CO_2$ into the atmosphere during the decarbonatization process in the kiln as part of the chemical reaction required for clinker production [4–6]. As shown in Figure 1, the decarbonatization process, which precedes calcination in cement manufacturing, emits substantial amounts of $CO_2$ due to the decomposition of limestone. It is estimated that $CO_2$ emissions from this process account for approximately 60–65% of the total emissions in the cement production process [7–9]. In South Korea, clinker production has remained at an average of 43.2 million tons/year for the past five years, requiring the consumption of approximately 71.3 million tons of raw materials annually [10]. As shown in Table 1, the use of limestone in the cement manufacturing process in South Korea averages 64.2 million tons/year, resulting in annual $CO_2$ emissions of 24.2 million tons. If current trends continue, cumulative $CO_2$ emissions are projected to reach 630 million tons by 2050.

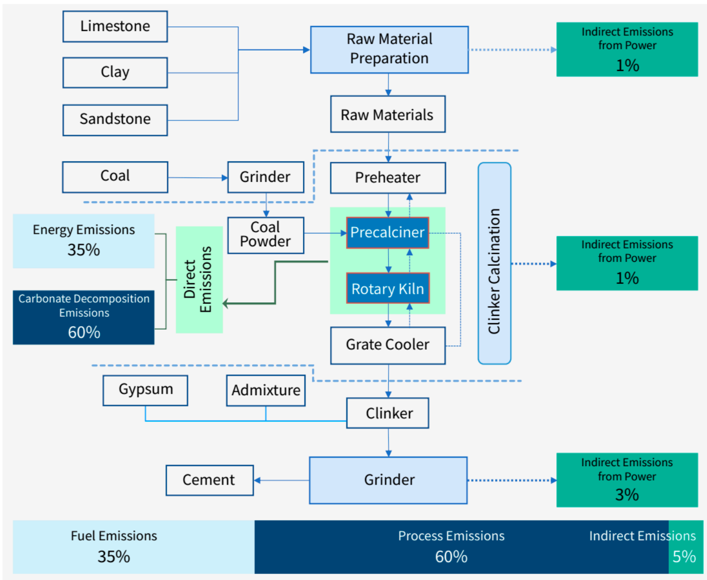



**Figure 1.** $CO_2$ emissions from cement manufacturing process [7].

**Table 1.** Annual clinker production and limestone-related $CO_2$ emissions in South Korea (2019–2023).

| Category | 2019 | 2020 | 2021 | 2022 | 2023 | Average |
|---|---|---|---|---|---|---|
| Clinker Production (Mt) | 45.9 | 41.8 | 43.4 | 42.8 | 41.9 | 43.2 |
| Mixed Raw Materials Usage (Mt) | 75.8 | 69.1 | 71.7 | 70.8 | 69.3 | 71.3 |
| Limestone Usage (Mt) | 68.2 | 62.2 | 64.6 | 63.7 | 62.3 | 64.2 |
| Limestone-origin $CO_2$ generation (Mt) | 25.7 | 23.4 | 24.3 | 24.0 | 23.5 | 24.2 |

One of the most effective methods to reduce carbon emissions in cement production is to lower the clinker factor by reducing clinker production and usage, thereby increasing the use of blended cement with lower clinker content. Numerous studies on low-carbon blended cement, such as Portland limestone cement, calcined clay-based blended cement, multi-component blended cement, and calcareous fly ash-based cement with pozzolanic additives (e.g., fumed silica, $Na_2SiO_3$), have been globally published [11–13]. Research related to so-called supplementary cementitious materials (SCMs) can be considered highly advanced [14,15]. However, to significantly reduce the cement industry's total $CO_2$ emissions, it is necessary to conduct further research focused on reducing emissions from the decarbonatization process, which constitutes a major portion of the industry's carbon footprint. The high carbon emissions from decarbonatization are attributed to the carbon content in the raw materials. Therefore, developing technologies that use already decarbonized materials as clinker raw materials is crucial. In this study, we focused on domestically generated waste concrete fine powder.

At the end of its service life, concrete becomes construction waste, with waste concrete accounting for the largest portion (62%) of construction waste, generating over 47.5 million tons in 2022 [16]. Waste concrete consists of cement paste and aggregates. Numerous studies have examined waste concrete to address the domestic shortage of aggregates in South Korea [17,18]. The process of producing recycled aggregate from waste concrete is multi-step, typically involving various crushing and grinding stages and the use of debris removal equipment. Most production processes employ high-impact forces on waste concrete to separate aggregates from cement paste, though this method does not efficiently remove all cement paste attached to the aggregate surface and may damage the aggregate [19–21]. As a result, recycled aggregates produced by this method are of lower quality and have limited applications due to the significant hardened cement paste adhering to them. To address this technical limitation, several studies have focused on peeling and crushing technologies that leverage the differences in strength between cement paste and aggregates to achieve efficient separation [22–24]. These technologies aim to improve the final quality of recycled aggregates by separating cement paste without damaging the aggregates [25,26].

The process of separating aggregates from cement paste inevitably produces waste concrete fine powder, primarily composed of cement paste. Waste concrete fine powder consists of unhydrated cement and hydration products, such as calcium hydroxide and calcium silicate hydrate [27–29]. Although waste concrete powder exhibits some pozzolanic activity due to unreacted clinker and reactive silica from fine aggregates, it is primarily regarded as a filler [30–32]. However, because its chemical composition is similar to that of cement, using it as a clinker raw material rather than as an SCM may be more appropriate. Gastaldi et al. demonstrated the potential of using waste concrete powder as a clinker raw material based on laboratory-scale experiments in which they synthesized pure cement paste without impurities [33]. Zhutovsky et al. analyzed the phase changes in hydrated cement paste heat-treated at temperatures between 600 and 1450 °C, confirming the potential for its complete recovery as new clinker [34]. Additionally, Schoon et al. reviewed various classification and separation technologies for aggregates and fines from actual waste concrete, concluding that waste concrete powder could be used as a limestone substitute in clinker production [35]. Waste concrete fine powder comprises unhydrated cement and cement hydration products, as described above. Although certain hydration products may undergo recarbonation, most exist in a decarbonized state, making them suitable raw materials for clinker production, significantly reducing $CO_2$ emissions. However, the use of waste concrete powder as a limestone substitute in cement plants remains untested, and research is still limited.

In this study, we investigated the feasibility of utilizing waste concrete fine powder, a byproduct of recycled aggregate production, as an alternative raw material to limestone in clinker manufacturing. The distinct physical and chemical properties of waste concrete fine powder, including its decarbonized state and carbonation rate, are hypothesized to enable its effective substitution for limestone, which could potentially reduce $CO_2$ emissions and promote the recycling of construction waste. In South Korea, variations in recycled aggregate production systems, particularly in the type and frequency of crushers used, result in differing qualities of waste concrete fine powder. Accordingly, to evaluate its suitability as a clinker raw material, this study analyzed the physical and chemical properties of fine powders obtained from various recycling processes and quantified their carbonation rates. Furthermore, based on the carbonation rate, the potential $CO_2$ reduction achieved by replacing limestone with waste concrete fine powder was estimated, highlighting its significant environmental benefits. As a result, the findings contribute to advancing decarbonization strategies in the cement industry while also enhancing resource efficiency and mitigating environmental impacts.

## 2. Materials and Methods

### 2.1. Sample Collection

The waste concrete fine powder used in this experiment was collected from 20 intermediate treatment companies across South Korea. Based on the intended use of the aggregates, 12 samples were obtained from recycled aggregate production processes for road construction, and 8 samples were obtained from recycled aggregate production processes for concrete. The regional distribution of the recycled aggregates produced from waste concrete, categorized based on their intended use, is shown in Figure 2.

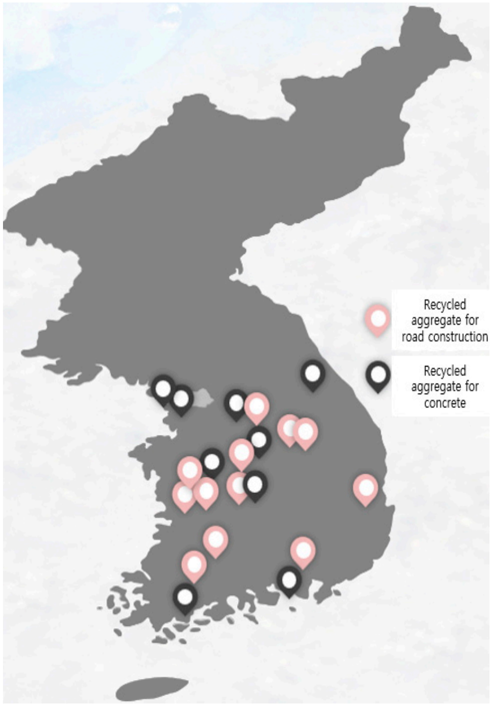



**Figure 2.** Location of concrete recycling plants.

### 2.2. Experimental Plan and Method

Table 2 shows the experimental plan for this study. To collect the fine powder generated from waste concrete, recycled aggregates produced in various regions across the country were sieved to collect powder particles smaller than 300 μm, using the vibrating sieve classifier shown in Figure 3. The collected fine powder was analyzed for chemical composition, particle size distribution, and carbonation rate. The chemical composition was measured according to KS L 5222, *Chemical Analysis Method of Cement by X-ray Fluorescence* [36]. Additionally, the particle size distribution was analyzed using laser diffraction technology, following ISO 13320, *Particle Size Analysis—Laser Diffraction Methods* [37]. This method, which measures the angle change of scattered light based on the intensity of light passing through dispersed fine particle samples, was applied to measure particle sizes within a range of 10 nm to 3.5 mm. The carbonation rate was measured according to ASTM E1131, *Standard Test Method for Compositional Analysis by Thermogravimetry* [38], and determined by quantifying the conversion of calcium-based hydrates to calcium carbonate through the measurement of mass changes in the 600–900 °C range.

**Table 2.** Experimental plan.

| Analytical Samples | Target Sample | Test Items |
|---|---|---|
| 20 samples | Less than 300 μm waste concrete fine powder | • Chemical composition<br>• Particle size distribution<br>• Carbonation rate |

**Figure 3.** Vibrating sieve classifier.

### 2.3. $CO_2$ Reduction Calculation

In this study, we evaluated the environmental benefits of replacing limestone with waste concrete fine powder in clinker production. The $CO_2$ reduction potential achieved by replacing limestone with waste concrete fine powder was calculated using Equation (1). The parameters used in the calculation are defined as follows:

$$\Delta CO_2 = \left(E_c \times E_{cc} \times \left(1 - C_{wcp}\right) \times R_{sub}\right) \times Q_c \quad (1)$$

where

$\Delta CO_2$: *Total* $CO_2$ *reduction (tons)*
$E_c$: $CO_2$ *emission factor per ton of clinker*
$E_{cc}$: *Proportion of* $CO_2$ *emissions from* $CaCO_3$ *decarbonatization*
$C_{wcp}$: *Carbonation rate of waste concrete fine powder*
$R_{sub}$: *Substitution rate of waste concrete fine powder for limestone*
$Q_c$: *Total domestic clinker production*

## 3. Results and Discussion

### 3.1. Process Analysis

Table 3 presents the characteristics of typical crushers used by intermediate processing companies, i.e., construction waste recycling plants, in South Korea. The density and absorption rate of recycled aggregates produced from waste concrete vary depending on the amount of hardened cement paste attached to the aggregate surface. As the cement paste content increases, the density decreases while the absorption rate increases, leading to a deterioration in concrete quality. Recycled aggregates produced from waste concrete are generally classified by use into three categories: aggregates for concrete, road construction, and embankment soil. Specifically, aggregates crushed in the first and second stages are typically used for embankment or soil covering; those crushed in the third and fourth stages are used for road construction, while aggregates crushed in the fourth stage and beyond are utilized for concrete production.

**Table 3.** Types and functions of crushers used in concrete recycling plants.

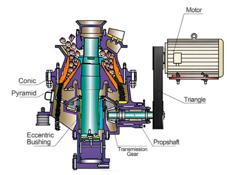
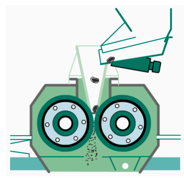
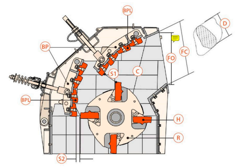
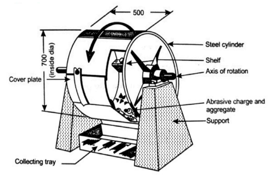
| Principle | Kind | Feature | Shape |
|---|---|---|---|
| Compressive force | Jaw crusher and cone crusher | Crushes concrete blocks to a specific size; cone crusher uses spiral grooves for secondary and tertiary crushing |  |
| | Roll crusher | Crushes materials using two rotating rods, typically for stone powder production |  |
| Impact force | Impact and hammer | Throws aggregate by rotational force, applying impact to crush or peel the surface |  |
| Shear force | Abrasion | Uses friction to peel the surface of aggregates and effectively remove surface paste |  |

Table 4 presents the types of crushers, grinders, and the number of crushing stages at 20 concrete recycling plants in South Korea where waste concrete samples were collected. These plants were categorized based on the final product's intended use. An analysis of the crushers, grinders, and crushing stages for each product type revealed that plants producing aggregates for road construction generally employed two or three stages of crushing, using jaw and cone crushers. In this process, large chunks of waste concrete are first crushed by a jaw crusher, followed by a cone crusher to remove cement paste from the aggregate surface.

Plants producing aggregates for concrete typically operate four to six crushing/grinding stages. Initially, they use jaw and cone crushers to reduce the size of the waste concrete, followed by multi-stage crushing and grinding to achieve proper particle size and quality. For concrete aggregates, the crushing and grinding process is applied four or more times to remove the cement paste attached to the aggregate, ensuring that the recycled aggregate meets density and absorption rate standards. Abrasion crushing machines are used to effectively separate the cement paste. Traditional crushing and grinding equipment applies high compression and impact forces, which are inefficient for selectively removing cement paste from the aggregate surface and can lead to issues such as destruction, cracking, and wear of the original aggregate. To address these challenges and efficiently separate the cement paste, various abrasion crushing machines are employed at plants producing recycled aggregates for concrete.

**Table 4.** Crushing times and processes of the 20 domestic concrete recycling plants.

| Final Production | Company Name | | Crushing Times | Process * |
|---|---|---|---|---|
| Recycled aggregate for road construction | 1 | HyundaiENP | 3 | J-C-C |
| | 2 | ENF | 2 | J-C |
| | 3 | Dongyoung | 3 | J-J-C |
| | 4 | Asan | 3 | J-C-C |
| | 5 | Yeil | 3 | J-C-I |
| | 6 | Muhan | 2 | J-I |
| | 7 | Jungdo | 2 | J-C |
| | 8 | Samsung | 3 | J-J-C |
| | 9 | Kaeam | 3 | J-J-C |
| | 10 | Dooseung | 3 | J-J-C |
| | 11 | Uchang | 3 | J-J-C |
| | 12 | Hankyul | 3 | J-J-C |
| Recycled aggregate for concrete | 13 | Younghung | 5 | J-J-C-C-I |
| | 14 | Bangtae | 6 | J-J-C-I-I-A |
| | 15 | Samsam | 5 | J-J-C-C-A |
| | 16 | SeoulENP | 3 | J-C-A |
| | 17 | HankangEMP | 6 | J-J-C-C-I-A |
| | 18 | Supero | 6 | J-J-C-R-R-I |
| | 19 | Jungang | 5 | J-J-C-S-S |
| | 20 | Kunhung | 4 | J-J-C-A |

* J—Jaw crusher; C—Cone crusher; I—Impact crusher; R—Roll crusher; S—Sand crusher; A—Abrasion crusher.

The number of crushing processes significantly impacts the final quality of the recycled aggregates. Recycled aggregate production plants in South Korea typically perform between two and six crushing stages, with the majority employing an average of three to four stages. Aggregates for road construction generally undergo fewer crushing processes (mainly two to three stages), while aggregates for concrete production require more complex processes, involving four or more crushing stages. This difference is attributed to the higher quality requirements for concrete aggregates.

Recycled aggregate production plants in South Korea predominantly utilize high-strength crushing equipment, e.g., double jaw crushers, ensuring that the initial strength of the material is maintained while enabling efficient recycling. Furthermore, specialized equipment like abrasion crushers is employed to produce high-quality recycled aggregates for concrete, enhancing the durability and overall quality of the end product. These processing characteristics illustrate that Korea's recycled aggregate industry not only prioritizes resource conservation and environmental protection but also focuses on producing high-quality recycled materials.

### 3.2. Chemical Composition

The chemical composition of waste concrete fine powder collected from 20 domestic intermediate treatment plants for construction waste was analyzed using X-ray fluorescence (XRF), with the results presented in Table 5. The analysis revealed that $SiO_2$ constitutes the largest proportion, ranging from 40% to 60%, while CaO constitutes 15% to 30%. All measured components correspond to the typical chemical composition of cement paste.

**Table 5.** Chemical composition of waste concrete fine powder.

| | Sample | CaO | $SiO_2$ | $Al_2O_3$ | MgO | $K_2O$ | $Na_2O$ | F | Cl | Others |
|---|---|---|---|---|---|---|---|---|---|---|
| Recycled aggregate for road construction | 1 | 31.28 | 43.31 | 12.81 | 2.01 | 2.31 | 0.89 | 0.49 | 0.05 | 6.85 |
| | 2 | 31.67 | 42.45 | 11.57 | 3.17 | 2.28 | 1.19 | 0.63 | 0.24 | 6.80 |
| | 3 | 27.59 | 46.50 | 13.39 | 2.38 | 2.34 | 1.09 | 0.49 | 0.03 | 6.20 |
| | 4 | 27.39 | 44.47 | 12.76 | 2.59 | 2.45 | 0.93 | 0.63 | 0.04 | 8.74 |
| | 5 | 29.86 | 46.84 | 11.41 | 1.70 | 2.84 | 0.56 | 0.25 | 0.06 | 6.48 |
| | 6 | 30.98 | 44.28 | 11.38 | 2.10 | 2.80 | 0.83 | 0.52 | 0.09 | 7.02 |
| | 7 | 33.98 | 42.42 | 10.52 | 1.92 | 2.57 | 1.12 | 0.34 | 0.03 | 7.10 |
| | 8 | 33.06 | 41.60 | 12.12 | 1.93 | 2.94 | 1.07 | 0.65 | 0.07 | 6.55 |
| | 9 | 30.15 | 45.25 | 11.65 | 2.06 | 2.91 | 1.04 | 0.35 | 0.06 | 6.54 |
| | 10 | 29.43 | 43.22 | 12.87 | 2.11 | 2.35 | 1.43 | 0.56 | 0.07 | 7.95 |
| | 11 | 28.11 | 43.37 | 13.93 | 2.26 | 2.89 | 1.21 | 0.36 | 0.07 | 7.80 |
| | 12 | 26.91 | 47.29 | 12.66 | 2.16 | 2.90 | 1.18 | 0.50 | 0.03 | 6.35 |
| | standard deviation | 2.17 | 1.79 | 0.94 | 0.37 | 0.26 | 0.21 | 0.12 | 0.05 | 0.73 |
| Recycled aggregate for concrete | 13 | 20.24 | 50.44 | 13.85 | 1.91 | 3.80 | 1.95 | 0.46 | 0.46 | 6.90 |
| | 14 | 31.43 | 41.59 | 12.60 | 2.12 | 2.70 | 0.87 | 0.54 | 0.10 | 8.07 |
| | 15 | 16.74 | 51.26 | 14.64 | 3.24 | 2.50 | 2.27 | 0.44 | 0.05 | 8.87 |
| | 16 | 11.07 | 58.05 | 17.57 | 1.64 | 4.11 | 2.36 | 0.46 | 0.05 | 4.68 |
| | 17 | 13.67 | 53.86 | 16.28 | 1.52 | 5.05 | 1.02 | 0.61 | 0.15 | 7.83 |
| | 18 | 26.98 | 50.28 | 11.59 | 1.37 | 3.49 | 1.48 | 0.47 | 0.02 | 4.32 |
| | 19 | 20.68 | 56.05 | 11.55 | 1.45 | 3.47 | 1.11 | 0.78 | 0.05 | 4.85 |
| | 20 | 6.45 | 58.76 | 14.29 | 2.41 | 6.25 | 1.78 | 0.61 | 0.04 | 9.41 |
| | standard deviation | 7.69 | 5.17 | 2.01 | 0.59 | 1.15 | 0.54 | 0.11 | 0.14 | 1.88 |

Figure 4 illustrates the chemical composition of waste concrete fine powder collected from final products at domestic intermediate treatment plants. The fine powder obtained from plants producing recycled aggregate for road construction exhibited the highest CaO content, approximately 28% to 31%. Conversely, the fine powder from plants producing concrete aggregate showed a lower CaO content, averaging 20%. This distinct difference in chemical composition indicates that the intended use of the aggregate significantly affects the composition of the fine powder. The relatively higher CaO content and lower $SiO_2$ content in the fine powder from road construction aggregates suggest a higher cement paste residue, which remains during the recycling process. On the other hand, the more intense crushing and separation processes for concrete aggregate result in the removal of cement components, leaving behind primarily aggregate material.

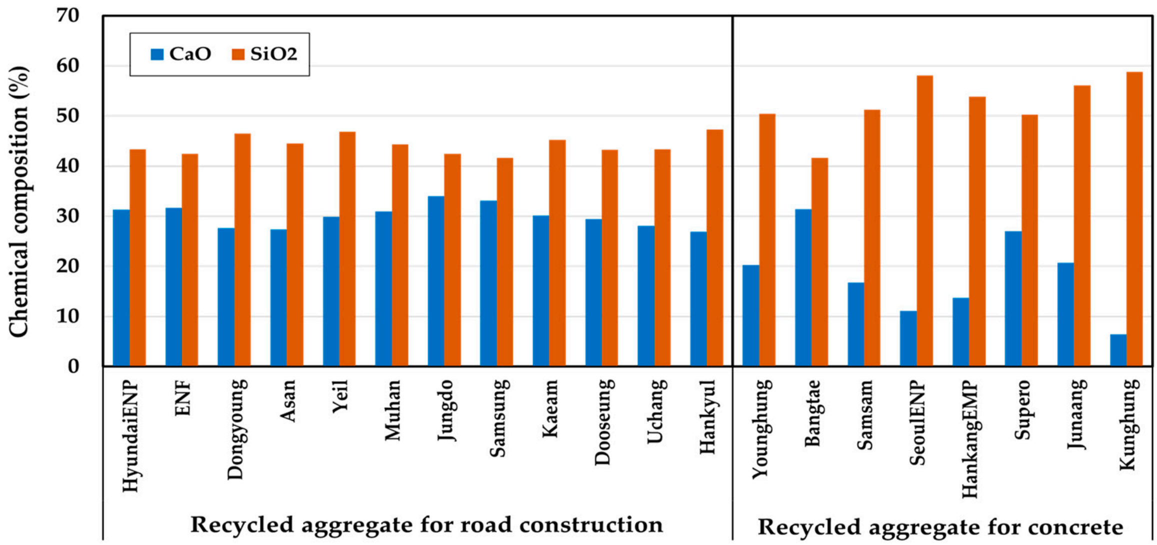



**Figure 4.** CaO and $SiO_2$ content of waste concrete fine powder.

The chemical composition of waste concrete fine powder exhibits distinct variability between the two groups. Fine powder derived from road construction aggregates demonstrates relatively consistent chemical properties, with a standard deviation of 2.17% for CaO and 1.79% for $SiO_2$. This low variability indicates that fine powders from road aggregates are more predictable in their performance, making them a stable alternative material for partial limestone substitution in clinker production. In contrast, fine powder obtained from concrete aggregates exhibits significantly higher variability, with a CaO standard deviation of 7.69% and a $SiO_2$ standard deviation of 5.17%. This increased variability, primarily attributed to more complex processing methods, presents challenges in achieving consistent clinker properties and underscores the necessity of implementing strict quality control measures to ensure uniform chemical composition and reliable performance.

Numerous studies [39,40] have indicated a proportional relationship between the amount of attached cement paste and the absorption rate in recycled aggregate. Therefore, the degree of cement paste adhesion plays a critical role in determining the quality of recycled aggregate. To meet the absorption and density requirements for recycled concrete aggregate, the aggregate typically undergoes additional processing to reduce its density and increase its absorption, aimed at maximizing the removal of cement paste. As a result, recycled concrete aggregate with minimal cement paste tends to demonstrate superior aggregate quality. This also explains the relatively lower CaO content in the waste concrete fine powder collected from concrete aggregate, where much of the cement paste has been removed. Additionally, during multi-stage crushing and separation processes to remove adhered cement paste, the original aggregate undergoes further fragmentation and abrasion, leading to an increase in $SiO_2$ content in the fine powder.

Figure 5 depicts the variation in CaO and $SiO_2$ content in waste concrete fine powder as a function of the number of crushing stages. As the number of crushing stages increases, the CaO content decreases, while the $SiO_2$ content increases. This trend clearly suggests that the chemical properties of waste concrete fine powder can be controlled by selecting appropriate crushing processes. Fine powder generated from fewer crushing stages—such as that from road construction aggregate production—tends to have a higher CaO content due to more effective separation of cement paste. Therefore, to effectively utilize waste concrete fine powder as a clinker raw material, it would be ideal to use fine powder from road construction aggregate production, where fewer crushing stages are applied. This powder, with its higher CaO content, can provide the necessary components for clinker production while contributing to resource conservation and reducing carbon emissions in the cement industry.

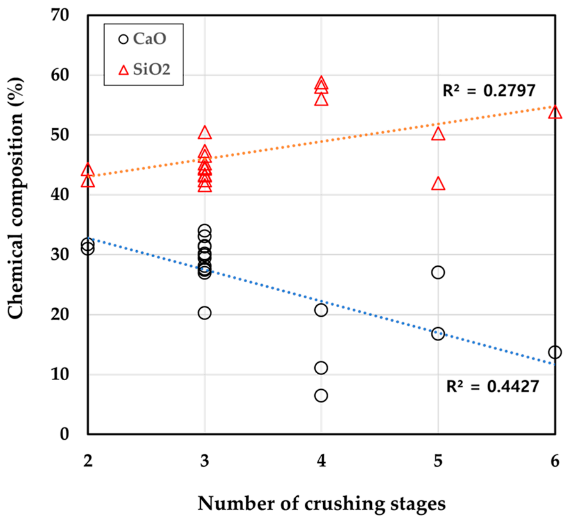



**Figure 5.** CaO and $SiO_2$ content in waste concrete fine powder based on crushing stages.

Figure 6 illustrates the relationship between the contents of CaO and $SiO_2$, which vary significantly depending on the degree of cement paste separation in the recycled aggregate. When the cement mortar is efficiently separated from the recycled aggregate, the CaO content in the fine powder increases. Conversely, when the separation of the cement mortar is insufficient, residual $SiO_2$ is introduced into the fine powder, resulting in a relative increase in $SiO_2$ content and a decrease in CaO content. This phenomenon shows that changes in CaO and $SiO_2$ content are inversely related, with the coefficient of determination ($R^2$) calculated to be 0.8685, indicating a strong negative correlation.

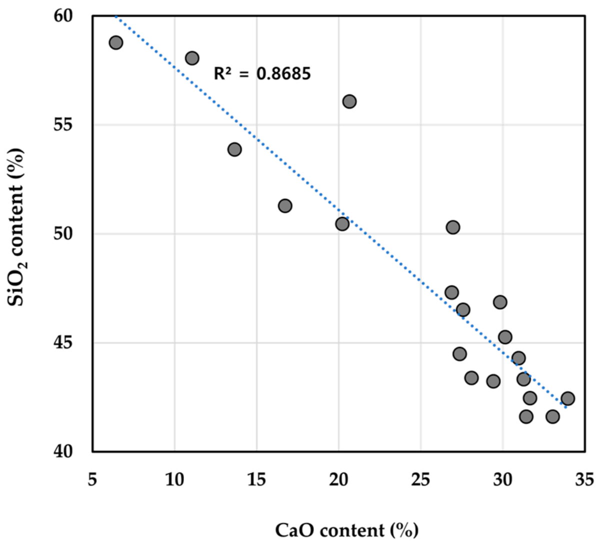



**Figure 6.** Relationship between CaO and $SiO_2$ content of waste concrete fine powder.

Additionally, the sum of CaO and $SiO_2$ in waste concrete fine powder tends to remain constant at 70–75%, demonstrating that the chemical composition of waste concrete fine powder is predominantly influenced by these two components. This analysis provides important insights into understanding the characteristics of recycled aggregates and waste concrete fine powder, contributing to the prediction and optimization of the fine powder's performance.

### 3.3. Particle Size Distribution

Figure 7 illustrates the median particle size (D50) of the collected waste concrete fine powders. The D50 values of fine powders generated during the production of recycled aggregates for road construction generally range between 70 and 90 μm, with most samples displaying similar values, except for HyundaiENP (9.2 μm) and Dongyoung (108.26 μm). This trend suggests that the fine powders produced during the recycled aggregate production process for road construction exhibit a relatively consistent particle size distribution. In contrast, the D50 values of fine powders generated during the production of recycled concrete aggregates show significant variation between samples. For instance, Samsam (281.11 μm) and SeoulENP (259.02 μm) exhibited larger particle sizes, while Bangtae (18.48 μm) and Supero (14.27 μm) displayed much smaller particles. This result indicates that the particle size distribution of fine powders from recycled concrete aggregate production is more variable compared to those from road construction aggregate production.

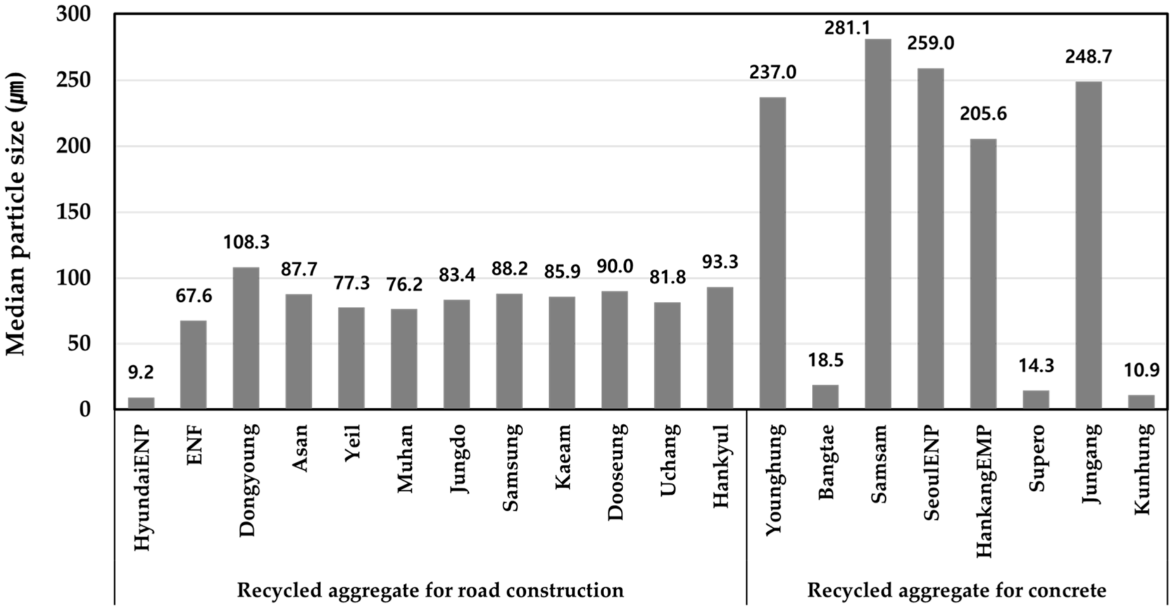



**Figure 7.** Median particle size of waste concrete fine powder.

Figure 8 shows the relationship between the number of crushing stages and the median particle size of the waste concrete fine powders. The results indicate that the particle size characteristics of waste concrete fine powders vary depending on the recycled aggregate production process. In the production of recycled aggregates for road construction, which typically involves two to three crushing stages, the particle size distribution was relatively consistent across samples. However, in the production of recycled concrete aggregates, which involves three to six crushing stages, no clear relationship between the number of crushing stages and particle size was observed. This suggests that the physical properties of the fine powders can differ significantly depending on the treatment methods used in each process.

Since we intended to examine the application of waste concrete fine powders as a substitute for limestone in clinker raw materials, the fine powders were mixed with other raw materials such as limestone, clay, and silica, and subjected to a grinding process. Typically, cement plants in Korea control the particle size of raw materials fed into the calciner for clinker production to ensure that no more than 12% of the material is retained in a 90 μm sieve. Considering this standard, the waste concrete fine powder collected from road construction aggregate production, which exhibits relatively stable particle size characteristics, shows slightly higher potential for use as a raw material in clinker.

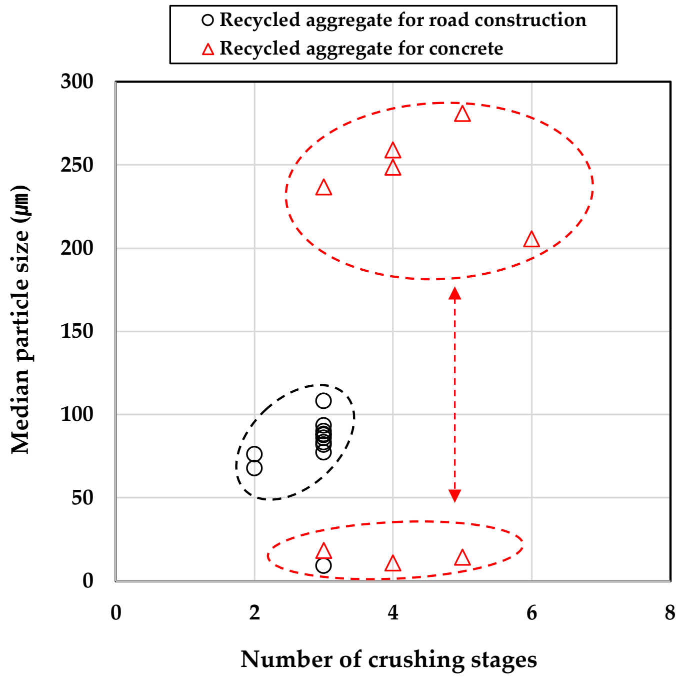



**Figure 8.** Relationship between number of crushing stages and median particle size.

### *3.4. Carbonation Rate*

To evaluate the feasibility of using waste concrete fine powder as a clinker raw material, recent studies [41–43] from the past few years utilizing real construction waste were reviewed. The physicochemical properties of the material analyzed in this study were found to align with those reported in these studies, confirming its potential for use as a raw material in clinker production. Nevertheless, as these studies did not investigate the carbonation rate—a key factor influencing $CO_2$ reduction—further evaluation of the carbonation rate is necessary.

The carbonation of concrete is generally described as the phenomenon in which carbon dioxide from the atmospheric environment penetrates the concrete, lowering the pH of the pore water and initiating rebar corrosion. While carbonation itself is not considered a significant issue for concrete as a structural material, it becomes problematic when the passive film protecting the rebar in the concrete is disrupted, leading to the activation of the rebar and its progression toward general corrosion. In general, concrete primarily produces hydration products such as calcium silicate hydrate (C-S-H) and calcium hydroxide through the hydration of cement, which contributes to its strength. In concrete, carbonation primarily affects calcium hydroxide and calcium silicate hydrate, leading to the formation of carbonation products such as calcium carbonate and silica gel, as shown in Equations (2) and (3) [44].

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{2}$$

$$xCaO{\cdot}ySiO_2{\cdot}zH_2O + xCO_2 \rightarrow xCaCO_3 + y(SiO_2{\cdot}tH_2O) + (z - yt)H_2O \tag{3}$$

Figure 9 represents the lime cycle, a fundamental process in the production and transformation of calcium-based materials, showing the cyclical transformation between limestone ($CaCO_3$), quicklime (CaO), and hydrated lime ($Ca(OH)_2$) [45]. Calcium carbonate is known to decompose in the temperature range of 600–900 °C, a process that can be accurately measured using thermogravimetric analysis. Therefore, to evaluate the carbonation rate in waste concrete fine powder, the amount of calcium carbonate formed in the powder was quantified using DT-TGA.

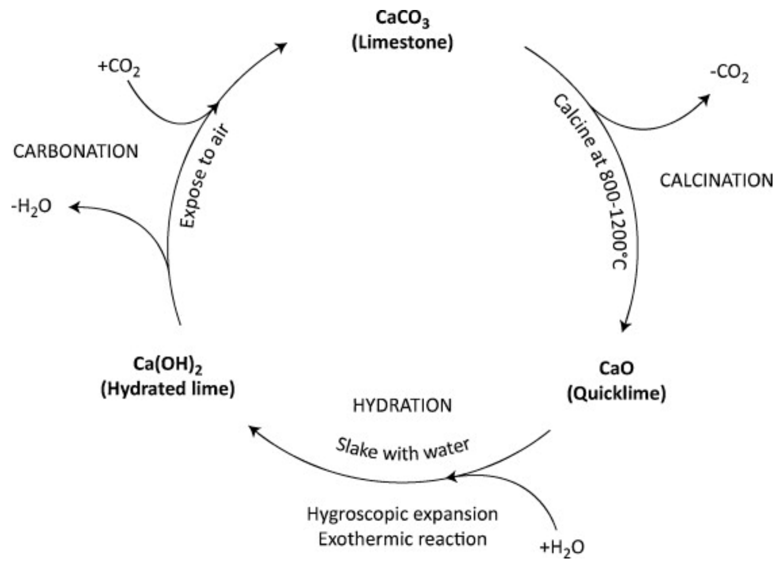



**Figure 9.** The lime cycle [45].

Figure 10 shows the carbonation rates of waste concrete fine powders produced in different recycled aggregate production processes. The carbonation rate of waste concrete fine powder is influenced by factors such as the materials, mix proportions, design strength, type of structure, location, and environmental conditions of the original concrete. For example, interior structures, well-waterproofed exterior structures, or concrete with high design strength tends to exhibit lower carbonation rates, whereas bridges, dams, or concrete exposed directly to the outdoors generally shows higher carbonation rates.

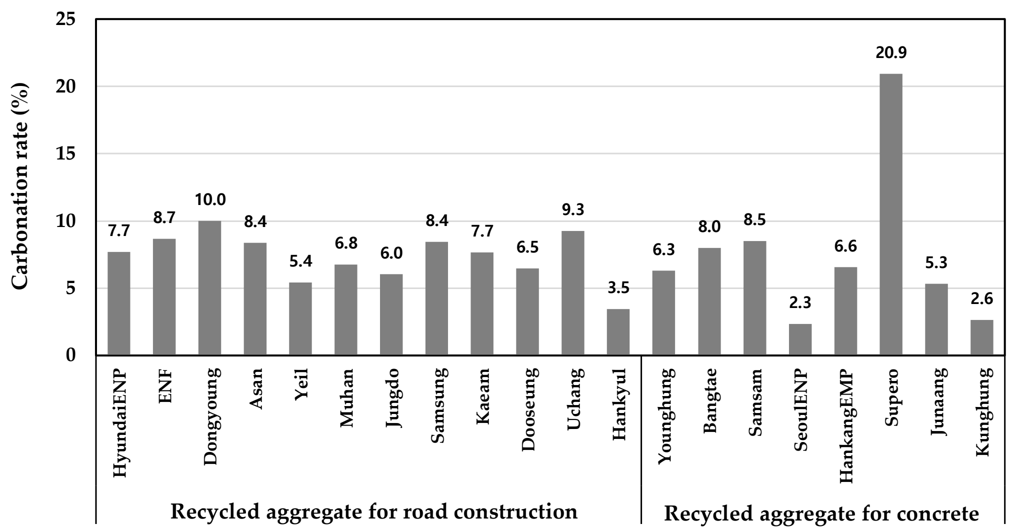



**Figure 10.** Carbonation rate of waste concrete fine powder.

In this study, the carbonation rates of the collected waste concrete fine powders were mostly below 10%, with an overall average of approximately 7.44%. This suggests that the carbonation rate in the waste concrete fine powders produced from various processes is generally within a similar range, indicating that they may have high potential for use as decarbonatization materials in clinker production. However, the Supero sample exhibited an exceptionally high carbonation rate of approximately 20.9%, which is likely due to prolonged exposure to moisture and the atmosphere before the concrete was demolished, leading to more extensive carbonation than in other samples.

Figure 11 compares the thermogravimetric analysis data for the HyundaiENP and Supero samples. The carbonation rate for each sample was calculated based on the mass loss of calcium carbonate in the 600–900 °C range. The HyundaiENP sample showed a relatively gradual mass loss in this temperature range, resulting in a carbonation rate of 7.7%, which is close to the overall average carbonation rate (7.4%) observed in this study. In contrast, the Supero sample exhibited a much steeper mass loss in the same temperature range, leading to a carbonation rate of 20.9%. This significant difference in carbonation rates highlights the influence of environmental exposure and the characteristics of the demolished concrete structures. The results emphasize the importance of considering these factors when evaluating the carbonation potential of recycled waste concrete fine powder.

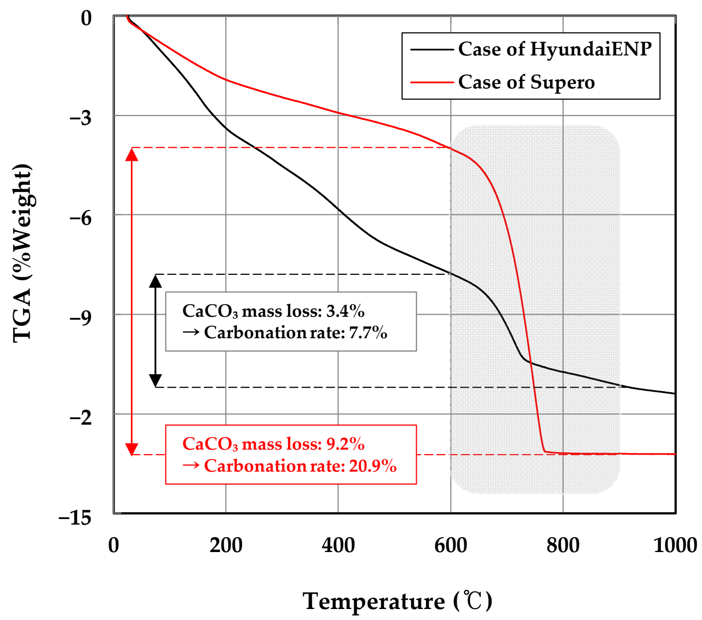



**Figure 11.** Comparison of carbonation rates for HyundaiENP and Supero samples.

### *3.5. Estimation of $CO_2$ Reduction*

Using the methodology described in Section 2.3, the $CO_2$ reduction was calculated to be approximately 952,560 tons, achieved through the following process. In the domestic cement industry, $CO_2$ emissions for producing 1 ton of clinker are approximately 0.84 tons, with 60% of these emissions resulting from limestone decarbonatization. This study analyzed the $CO_2$ reduction effect by replacing 5% of the limestone used in clinker production with waste concrete fine powder, assuming a carbonation rate of 7.44%. Based on the total clinker production of 42 million tons in 2023, this substitution results in an estimated reduction of 952,560 tons of $CO_2$ emissions, which represents a 3.34% decrease in total emissions from clinker production.

Looking ahead, further reductions in $CO_2$ emissions could be achieved by increasing the substitution rate of waste concrete fine powder or integrating this approach with other eco-friendly technologies to enhance its effectiveness. However, future studies should evaluate how the replacement of limestone with waste concrete fine powder influences fuel consumption and the temperature required for clinker burning. Additionally, a comprehensive life cycle assessment comparing the emissions associated with processing and transporting waste concrete to those from quarrying and crushing limestone is essential. Such research would provide a clearer understanding of the overall $CO_2$ reduction potential and the environmental advantages of incorporating waste concrete fine powder in clinker production.

## 4. Conclusions

The results of this study partially confirmed the hypothesis that waste concrete fine powder, with its distinct physical and chemical properties, can serve as a viable substitute for limestone in clinker production, reducing $CO_2$ emissions. The following conclusions were obtained.

(1) In South Korea, recycled aggregate production plants vary in the number of crushing stages and equipment used. It was found that road construction aggregate production plants typically involve two to three stages with the use of jaw and cone crushers, while concrete aggregate production plants involve four to six stages including additional grinding.
(2) Fine powders generated from recycled road aggregates showed higher CaO content (28–31%), indicating higher cement paste residue. In contrast, fine powders from recycled concrete aggregates contained lower CaO levels (around 20%) and higher $SiO_2$ content, reflecting the more intensive crushing process required to remove cement paste and produce high-quality aggregates.
(3) Fine powders from road construction aggregates had more consistent particle size distributions, while those from recycled concrete aggregates exhibited greater variability. This difference suggests that fine powders from road construction aggregates, with their stable particle size characteristics, may be more suitable for use in clinker production.
(4) The average carbonation rate of approximately 7.44% highlights the potential of replacing virgin limestone with calcium carbonate in the clinker production process, contributing to reduction in $CO_2$ emissions.
(5) Replacing 5% of limestone with waste concrete fine powder in clinker production led to an estimated $CO_2$ reduction of 952,560 tons, representing a 3.34% decrease in total $CO_2$ emissions from clinker production in 2023. This result underscores the potential of waste concrete fine powder to significantly contribute to the cement industry's decarbonization efforts.

In conclusion, the use of waste concrete fine powder offers a practical and effective strategy to address two critical challenges in the cement industry: reducing carbon emissions and managing construction waste. This approach enhances resource efficiency by repurposing a byproduct of recycled aggregate production, reducing reliance on quarried limestone, and optimizing material utilization. It also presents economic advantages by lowering raw material costs and minimizing waste management expenses. From an environmental perspective, the substitution decreases decarbonatization-related emissions, aligns with global sustainability goals, and promotes circular economy practices. Together, these benefits underscore the potential of integrating waste concrete fine powder into clinker production, contributing to a more sustainable and efficient construction industry.

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