Thermal activation of Multi-Recycled Concrete Powder as Supplementary Cementitious Material for Repeated and waste-free Recycling

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Abstract

The utilization of powder generated during the recycling process of concrete waste is considered crucial for achieving the complete recycling of concrete waste. This study investigated the effect of thermal activation on using recycled concrete powder (RCP), produced from repeated recycling of concrete, as a supplementary cementitious material. RCPs obtained from three cycles of concrete recycling were heat-treated at 200 °C, 400 °C, 600 °C, and 800 °C for 2 hours, and their chemical composition was analyzed before and after treatment. Subsequently, the RCPs were used to replace ordinary Portland cement in mortar by 10%, 20%, and 30%, and the fresh and hardened properties of the mortars, such as flow, mechanical strength, water absorption, and drying shrinkage, were tested. The results showed that as the replacement rate and the number of recycling cycles of RCP increased, the properties of the mortar deteriorated. However, heat treatment at 600 °C and 800 °C enhanced the strength and shrinkage resistance of the mortar. Specifically, the three-times RCP activated at 800 °C achieved mechanical performance similar to standard mortar at a 10% replacement rate without a decrease in strength grade. This study is expected to contribute to the repeatable recycling of concrete with zero waste.

Graphical abstract

Keywords: multi-recycling, closed-loop recycling, green cement, supplementary cementitous material

1. Introduction

The cement industry is one of the most carbon-intensive sectors, responsible for an estimated 7-8% of annual CO_2 emissions. This significant contribution exacerbates environmental concerns and highlights the urgent need for effective carbon footprint management. Reducing reliance on cement is crucial for decreasing the carbon emission, emphasizing the importance of supplementary cementitious materials (SCMs). However, traditional SCMs like fly ash and blast furnace slag are expected to decline in production (USGS, 2024), necessitating the discovery of new SCMs and the establishment of standards for their use (ASTM WK70466, 2019). Efforts are underway to utilize various industrial by-products and waste materials as SCMs, with construction and demolition (C&D) waste being a particularly significant potential source. In Europe, C&D waste constitutes about 36% of all solid waste, and globally, it exceeds 3 billion tons annually (Akhtar and Sarmah, 2018). Moreover, the amount of C&D waste is reported to be continuously increasing in several countries (Kim, 2021).

Concrete waste, a major component of C&D waste, is recognized as recyclable. It has been theoretically and technically demonstrated that concrete waste can be sorted and crushed to be recycled into coarse aggregates, fine aggregates, and powder, which have been used in constructions and commercialized products (Koshiro and Ichise, 2014). At this stage, a issue to address is the recycling of pre-recycled concrete, the multi-recycling of concrete. Researchers interested in this topic have explored how multi-recycling affect the properties of next-generation concrete. Recycled aggregate concrete, once recycled, has been crushed and reused in subsequent concrete mixtures as recycled coarse aggregates (H. Liu et al., 2022; Liu et al., 2021; Zhu et al., 2019b, 2016), recycled fine aggregates (Zhu et al., 2019a, 2018), and SCMs (Kim et al., 2023b; Kim and Jang, 2024, 2022). Generally, as concrete is recycled more times, the quality of the recycled materials degrades, leading to reduced mechanical performance and durability of concrete. For example, the density of natural coarse aggregates decreased from 2.59 g/cm^3 to 2.32 g/cm^3, 2.18 g/cm^3, and 2.12 g/cm^3 with each recycling stage (once, twice, and three times, respectively). As a result, the 28-day compressive strength of concrete using these aggregates was reduced by 3.2%, 4.7%, and 13.1% compared to concrete made with natural aggregates (Abreu et al., 2018). Similarly, the density of fine aggregates decreased from 2.59 g/cm^3 to 2.38 g/cm^3, 2.35 g/cm^3, and 2.26 g/cm^3 with each recycling cycle. Concrete made with 100% of these fine aggregates showed a 28-day compressive strength reduction of 23.0%, 29.1%, and 35.2% (Zhu et al., 2018). The performance loss in concrete caused by the use of multi-recycled aggregates has been reported to be mitigated through methods such as optimized mix design (Kim et al., 2023c, 2023a) and aggregate carbonation (H. Liu et al., 2022), and adjustments to aggregate replacemene rates (Marie and Quiasrawi, 2012). However, to the authors' knowledge, there has been little research on the fine fractions generated during the multi-recycling of concrete. In previous studies by the authors, the characteristics of multi-recycled concrete powders (multi-RCP) smaller than 150 μm and their effects on the properties of mortar (Kim et al., 2023b) and concrete (Kim and Jang, 2022) as SCMs were investigated. The studies found that as the number of recycling cycles increased, the RCP became more porous and had a lower density. Consequently, cementitious mixtures containing RCP from more recycling cycles exhibited reduced mechanical strength, elastic modulus, shrinkage and moisture absorption resistance compared to those with RCP from fewer recycling cycles. Therefore, for performance-based applications, it is necessary to modify these powders.

One method to modify the characteristics of the powder and enhance its reactivity is thermal activation. The thermal activation has been applied to various cementitious materials derived from cement paste (Carriço et al., 2020; Kim and Kim, 2023; Ma et al., 2022; Semugaza et al., 2023), waste concrete (Chen et al., 2024; Xu et al., 2021; Zhang et al., 2022), and mixed construction waste (Meng et al., 2021). Thermal activation is a temperature-dependent reversible process in which cement hydrates are transformed into dehydrated compounds similar to the original clinker at high temperatures (Xu et al., 2022). Several studies have observed that at temperatures around 600-800 ℃, the decomposition of C-S-H and the decarbonation of $CaCO_3$ form C_2S and CaO, which positively influence rehydration (Alonso and Fernandez, 2004; Semugaza et al., 2023). Zhang et al. (Zhang et al., 2022) reported that thermal activation of RCP improved compressive strength more significantly than chemical activator addition and mechanical grinding, and concluded that thermal activation is the most feasible and effective modification method.

Therefore, this study applies thermal activation to modify the characteristics of RCPs generated during the multi-recycling processes of concrete and utilizes the thermally activated powders as SCMs in cement mortar. The fresh, mechanical, and durability properties of RCP-based mortar are assessed and the cost-benefit and environmental impacts based on the experimental results are briefly discussed. The novelty of this study is the application of thermal activation to utilize multi-RCP as cement replacement, and the significance of this research lies in its support for the repeatable and waste-free recycling of concrete.

2. Materials and methods

2.1 Materials

In this study, cement, sand, water and three RCPs with different recycling cycles were used. Ordinary Portland cement (OPC) available in the local market and standard sand complying with the requirements of European standard EN196-1 were prepared, and tap water was used. The RCPs with different recycling cycles were obtained by collecting fine particles generated during the recycling process of concrete waste into recycled coarse aggregates. Specifically:

- RCP1: The once-recycled concrete powder was obtained from concrete where coarse aggregates consisted entirely of recycled aggregates (i.e., once-recycled coarse aggregate concrete, RCAC1). After performing the intended property tests, RCAC1 was crushed using a laboratory crusher. Through sieving, particles ranging from 4.75-19 mm were selected for use as coarse aggregates in twice-recycled coarse aggregate concrete (RCAC2), while particles smaller than 4.75 mm were milled to collect RCP1, which passed through a 150 μm sieve.
- RCP2: The twice-recycled concrete powder was obtained by crushing RCAC2. The detailed procedure was identical to that performed for obtaining RCP1. The coarse particles were used in thrice-recycled coarse aggregate concrete (RCAC3), while particles smaller than 150 μm were collected through milling.
- RCP3: The thrice-recycled concrete powder was obtained by crushing RCAC3, and the detailed procedure was identical to the preparation procedures for RCP1 and RCP2.

More detailed information regarding the preparation process and material characteristics of the RCPs can be found in the authors' previous study (Kim et al., 2023b, 2023a). The chemical composition and density are presented in Table 1, while thermogravimetric analysis results are shown in Figure 1.

Table 1. Chemical compositions of recycled concrete powders (Kim et al., 2023b)

	CaO	SiO_2	Fe_2O_3	Al_2O_3	SO_3	K_2O	MgO	TiO_2	Other	Density (g/cm^3)
RCP1	36.19	38.88	8.21	9.56	1.23	3.37	1.23	0.87	0.46	2.48
RCP2	44.50	32.09	8.56	8.14	1.35	2.81	1.14	0.89	0.52	2.38
RCP3	50.24	27.67	8.38	7.37	1.40	2.37	1.12	0.88	0.57	2.33

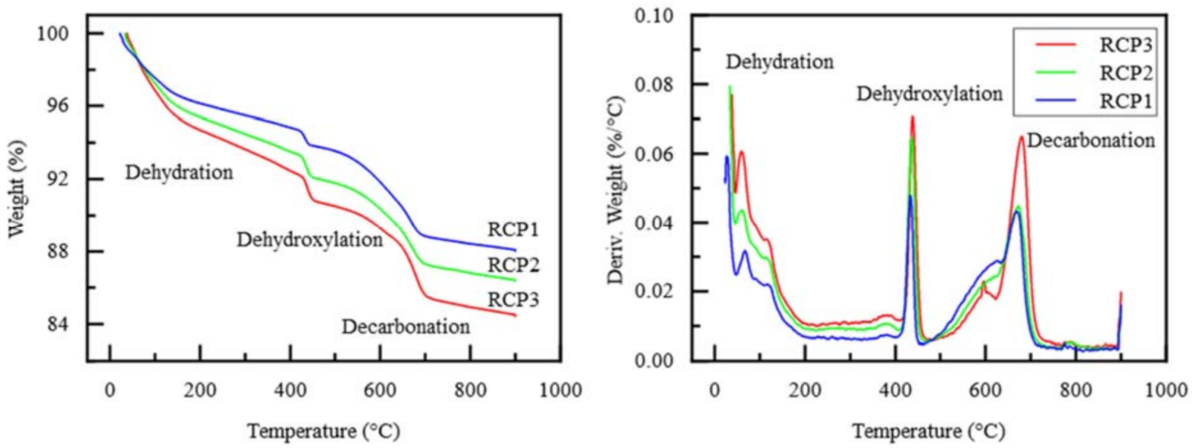

Figure 1. Thermogravimetric analysis of recycled concrete powders

2.2 Thermal activation of RCPs

To enhance reactivity, thermal treatment was conducted on the RCPs. The RCPs were heated in an electric furnace from room temperature (RT) to 200 °C, 400 °C, 600 °C, and 800 °C at a heating rate of 10 °C/min. Upon reaching each temperature, the RCPs were held for 2 hours and then cooled to room temperature inside the electric furnace. The RCP samples treated at various temperatures are shown in Figure 2. Before the treatment, all RCPs appeared gray in color, and after exposure to 200 °C, the powders turned a light gray. Subsequently, as the temperature increased to 400 °C, 600 °C, and 800 °C, the color gradually darkened, eventually showing a reddish tint. This discoloration occurs due to the oxidation of iron compounds (Hager, 2014; Ingham, 2009).

Figure 2. Multi-recycled concrete powders before and after heat treatment

2.3 Mortar compositions and specimen preparation

A total of 46 mortar mixtures, including standard mortar without RCP, were designed based on combinations of the following variables (Table 2): 3 RCPs with different recycling cycles (RCP1, RCP2, and RCP3), 3 replacement rates (10%, 20%, and 30%), and 5 thermal activation temperatures (RT, 200 °C, 400 °C, 600 °C, and 800 °C). The material proportions followed EN196-1. The water-to-binder (OPC and RCPs) ratio was 0.5, and the binder-to-sand ratio was 1:3. The mixing of materials was performed in an automatic mortar mixer. After each mixing, the fresh property of the mixtures were investigated, and specimens required for the intended hardened property tests were prepared and cured in water until testing.

In this study, the specimens are designated by a combination of 'recycling cycle-heat treatment temperature-replacement rate'. For example, a specimen containing 10% untreated RCP1 is referred to as 'R1-RT-10', while a specimen containing 30% RCP3 treated at 800 °C is referred to as 'R3-800-30'.

Table 2. Mortar preparation

Recycled powder	Replacement ratio (%)	Exposed temperature (°C)	Composition
RCP1, RCP2, RCP3	10, 20, 30	Non-treated (RT), 200, 400, 600, 800	Binder-sand ratio of 1:3 Water-binder ratio of 0.5

2.4 Experimental tests

To evaluate the applicability of thermally-activated multi-RCPs as SCMs, the phase composition of the RCPs before and after heat treatment was analyzed using X-ray diffraction (XRD), and the properties of the RCP-based mortars were assessed according to standardized test methods.

The XRD analysis was conducted using a Bruker AXS D8 Advance diffractometer (Bruker AXS GmbH D8 Advance, Karlsruhe, Germany) with the following parameters: a scanning range (2θ) from 10º to 90º, a scanning rate of 1º per minute, a step size of 0.05, and CuKα radiation (tube current of 40 mA, tube voltage of 40 kV, radiation wavelength of 1.54005 Å).

The workability of the fresh mixtures was assessed using the flow table test in accordance with ASTM C1437. Water absorption was determined by dividing the difference between the saturated surface dry weight and the oven-dry weight of the specimens by the oven-dry weight. For the mechanical strengths of the mixtures, 28-day compressive strength and flexural strength were evaluated using 50-mm cube specimens and 40 × 40 × 160 mm^3 prism specimens, respectively, according to ASTM C109 and ASTM C348. Drying shrinkage was measured on 25 × 25 × 285 mm^3 beam specimens according to ASTM C596. The specimens, demolded after 24 hours of casting, were cured in lime-saturated water for 48 hours. Following a total curing time of 72 hours, the specimens were stored in a chamber maintained at 23 ℃ and 50% relative humidity. Length changes were recorded using a digital length comparator at 1, 4, 11, 18, and 25 days (corresponding to 4, 7, 14, 21, and 28 days after casting). Each test was conducted on at least three specimens, and the average values along with the standard deviations are reported.

2.5 Cost and environmental analysis

The influence of using RCP as cement replacement on the cost and global warming potential (GWP) of concrete was briefly analyzed, assuming the production of 1m^3 of concrete with the following composition: 389 kg of cement, 1751 kg of aggregate, and 175 kg of water.

The cost of concrete ingredients was based on market prices investigated in the authors' previous research (Kim and Jang, 2022). The prices per tonne were as follows: 78,800 Korean won (KRW) for cement; 10,450 KRW for coarse aggregate; 11,540 KRW for fine aggregate; and 7,400 KRW for water. The oven used for activation had a power consumption of 10 kW, and the electricity cost for 10 kWh was set at 1,070 KRW, based on the industrial electricity rates listed on the Korea Electric Power Corporation (KEPCO) website (KEPCO, 2024). Seasonal and time-of-day rate variations were not considered.

The GWP of the materials was as follows: 0.885 CO_2-eq/kg for cement; 0.0032 CO_2-eq/kg for aggregate; and 0.25 CO_2-eq/kg for water. The hourly GWP of the oven used was calculated to be 4.24 CO_2-eq/kg according to information provided by KEPCO. For RCP activated at 800 °C, the release of CO_2 previously captured in the RCP due to decarbonation was factored in, with a value of 0.02 CO_2-eq/kg (He et al., 2019).

3. Results

3.1 X-ray diffraction of multi-recycled concrete powders

The XRD results of RCPs with different recycling cycles, before and after heat treatment at different temperatures, are shown in Figure 3. Despite differences in recycling cycles, the RCPs exhibit consistent peak patterns due to the identical raw materials used in the parent concretes. Quartz is the predominant mineral phase in the RCPs, while untreated RCPs (RCP1-RT, RCP2-RT, and RCP3-RT) clearly show hydration and carbonation products such as portlandite and calcite. For RPCs treated at 200 ℃ and 400 ℃, no significant phase changes were observed as the major compounds remained stable at these temperatures. As shown by TGA analysis, portlandite and calcite decompose around 430 ℃ and 670 ℃, respectively. Hence, in RCP treated at 600 ℃, the portlandite peak was not detected due to its decomposition. Additionally, a weak C_2S peak was identified, confirming the transformation of portlandite and hydration products into C_2S, consistent with findings in previous research (Bogas et al., 2020). In RCP treated at 800°C, the calcite peak was absent due to decarbonation, while the C_2S peak became more prominent. These observations are in good agreement with previous studies (Vashistha et al., 2023; Zhang et al., 2022). It is noteworthy that multi-RCPs also exhibit characteristic changes at high temperatures, suggesting that thermal activation could be a effective method for achieving repeated and complete recycling of concrete. Based on identified XRD peaks, it can be expected that mortars containing multi-RCPs activated at 600 ℃ and 800 ℃ will exhibit enhanced properties.

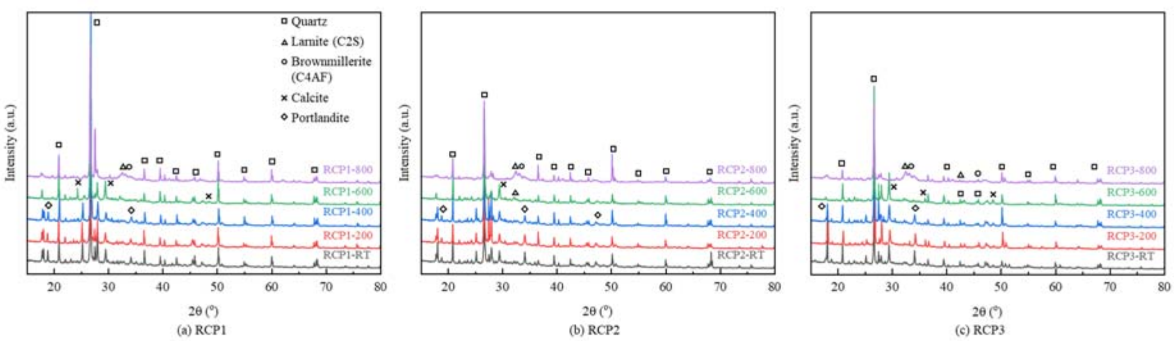

Figure 3. X-ray diffraction of recycled concrete powders before and after heat exposure

3.2 Flowability

The flow table results of the fresh mortar mixtures are presented in Figure 4, showing flow values ranging from 159 mm to 196 mm. The standard mortar exhibited the highest flow, while the flow decreased with increasing recycling cycle, replacement rate, and activation temperature of the RCP, reaching the lowest value at R3-800-30. As the RCP replacement rate increased from 10% to 30%, the flow decreased by 4.4% (from R1-600-10 to R1-600-30) and up to 9.4% (from R3-RT-10 to R3-RT-30). With the increase in recycling cycle from R1 to R3, the flow decreased by 2.6% (from R1-600-20 to R3-600-20) and up to 8.5% (from R1-800-30 to R3-800-30). Factors such as the irregular shape, high porosity, and rough texture of the RCP resist particle movement within the mixture, reducing flow (Jiang et al., 2022). These factors, which generally negatively affect the rheological properties of mixture, become more pronounced as the recycling cycle increases (Kim et al., 2023b). Furthermore, as the activation temperature of the RCP increased from 200 °C to 800 °C, the flow value decreased by 1% (from R1-RT-30 to R1-800-30) and up to 6.5% (from R2-RT-20 to R2-800-20). Previous studies have indicated that substances such as C_2S, formed during heat treatment, can participate in hydration reactions, thereby reducing free water and slightly decreasing the workability of fresh mixtures (Kim and Kim, 2023; Wu et al., 2021). Despite these reductions, it is noteworthy that all mixtures maintained adequate workability for specimen preparation.

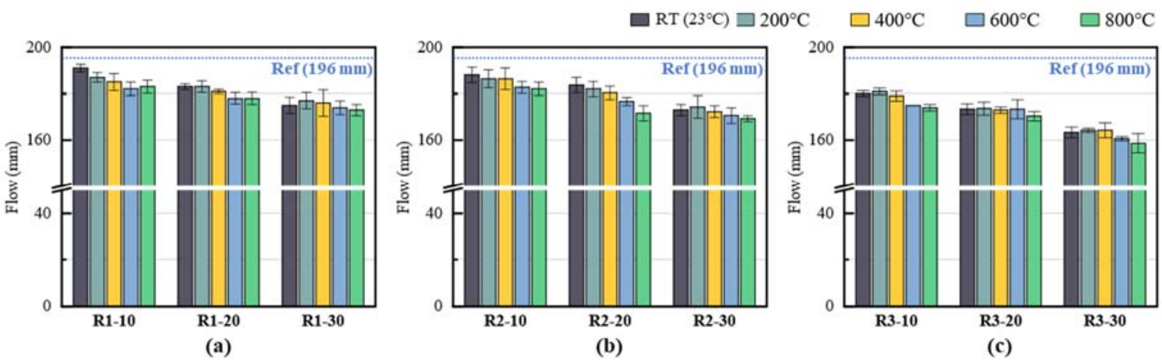

Figure 4. Fluidity of mortar with multi-recycled concrete powders

3.3 Mechanical strength

The 28-day compressive strengths of mortars containing RCPs are shown in Figure 5, with values ranging from 30.0 MPa to 55.5 MPa. The compressive strength of mortar containing untreated RCP decreases as the replacement rate increases. For mortars with RCP1 at replacement rates of 10%, 20%, and 30%, the 28-day compressive strengths decreased by 0.1%, 22.9%, and 34.3%, respectively, compared to the standard mortar. This reduction becomes more pronounced with an increasing number of recycling cycles. At the same replacement rates, the compressive strength reductions for mortars containing RCP2 are 3.6%, 28.2%, and 36.9%, while for mortars containing RCP3, the reductions are 6.5%, 36.4%, and 44.3%. This decrease is attributed to the low reactivity of RCP and the dilution effect of cement due to RCP replacement, consistent with previous studies (Kim et al., 2023b; Kim and Jang, 2022).

Thermal treatment of RCP at 200 ℃ and 400 ℃ did not significantly affect the compressive strength of the mortar. However, RCP treated at 600 ℃ and 800 ℃ resulted in a clear increase in strength. This enhancement was consistently observed in the mortars with multi-RCPs. Using RCP treated at 600 ℃ increased the compressive strength by 2.5% (R1-600-10) to 10.6% (R3-600-30), while RCP treated at 800 ℃ increased the compressive strength by 3.2% (R1-800-20) to 19.3% (R3-800-20). The highest strength, under the same replacement rate and recycling cycle, was achieved with RCP treated at 800 ℃, aligning with the optimal temperature range reported in other research (Ma et al., 2023).

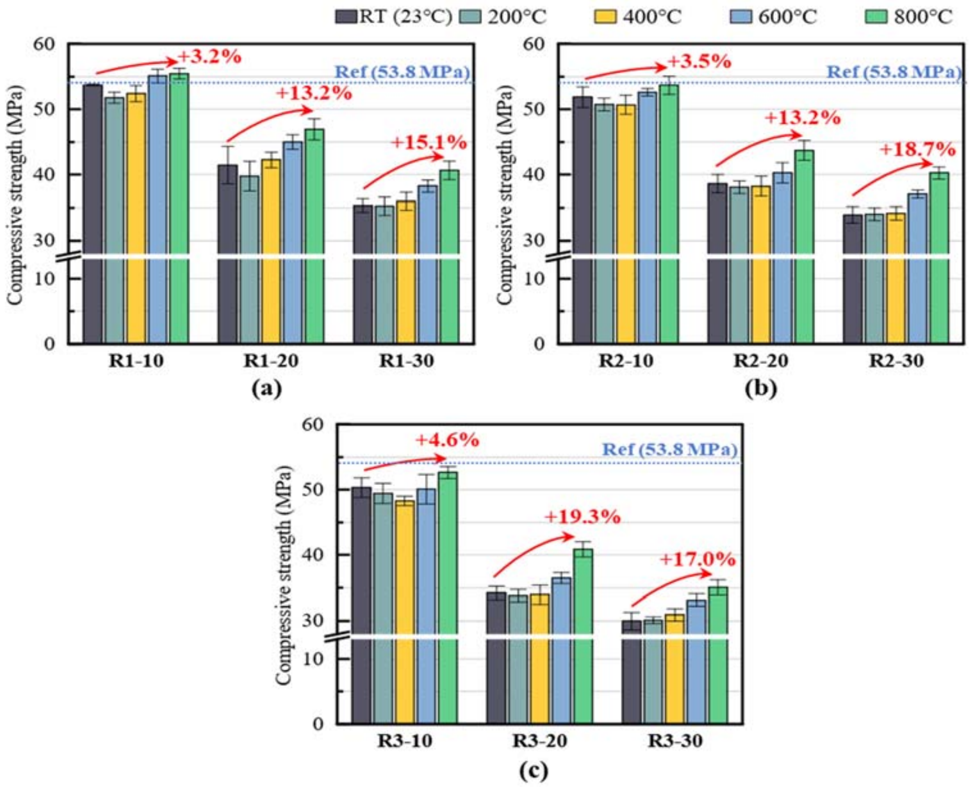

Figure 5. 28-day compressive strength of mortar with multi-recycled concrete powders

Figure 6 represents the compressive strength of mortar on a relative scale with respect to temperature. It reaffirms that thermal activation at 600 ℃ and 800 ℃ significantly enhances compressive strength. As shown in the figure, the efficacy of thermal activation is minimal at a 10% replacement rate but becomes more pronounced at 20% and 30%. Therefore, to efficiently utilize thermally activated RCP, a replacement rate of 20%-30% is recommended. However, higher replacement rates of OPC with RCP can lead to a reduction in absolute strength. Thus, adjusting the replacement rate may be necessary depending on the desired strength and objectives of the cement-based materials.

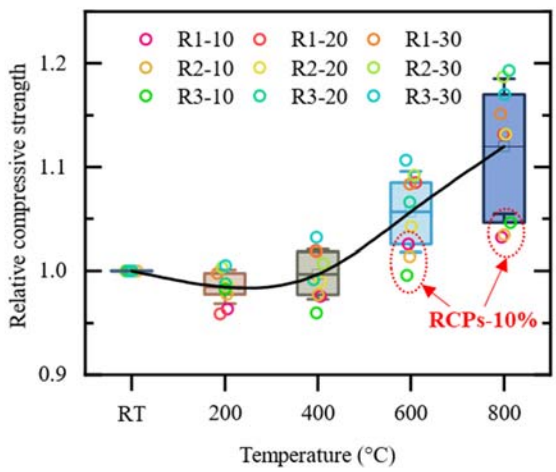

Figure 6. Relative compressive strength of mortars with respect to RCP treatment temperature

The flexural strength test results mirrored the compressive strength results: (i) the flexural strength of mortars containing untreated RCP was reduced by 8.3% (R1-RT-10%) to 26.8% (R3-RT-30%) compared to standard mortar; (ii) the use of RCP activated at 600 ℃ and 800 ℃ enhanced the flexural strength, with the most significant improvement observed in mortars containing 800 ℃-activated RCP, which increased the flexural strength by 4.7% to 16.1%, as shown in Figure 7.

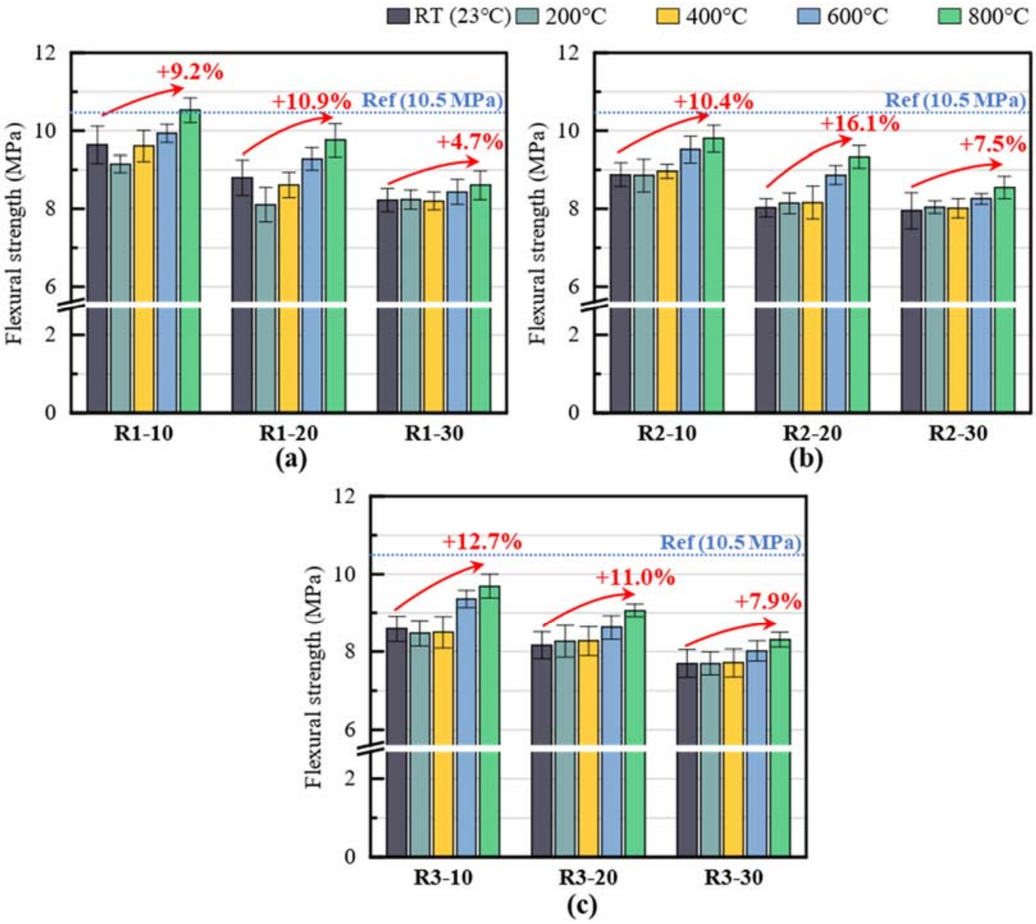

Figure 7. 28-day flexural strength of mortar with multi-recycled concrete powders

The enhancement in mechanical strength is attributed to the phase changes in RCP at high temperatures, as identified by XRD analysis. The C_2S formed after heat treatment at 600 °C exhibits high rehydration activity (Ji et al., 2021), which promotes hydration and thus increases the mechanical strength of the mortar. The superior strength of the mortar incorporating RCP activated at 800 °C is due to the stronger peak of C_2S observed after heat treatment at this temperature.

3.4 Drying shrinkage

The drying shrinkage test results, measured according to ASTM C596, are presented in Figure 8. Each individual graph in the figure represents the drying shrinkage of mortar with RCPs before and after heat treatment, including standard mortar. The three horizontally aligned graphs (i.e., (a), (b), (c)) illustrate different replacement ratios of RCP within the same recycling cycle (i.e., 10%, 20%, 30%), while the three vertically aligned graphs (i.e., (a), (d), (g)) show RCPs with different recycling cycles (i.e., RCP1, RCP2, RCP3) at the same replacement ratio.

As shown in each graph, RCP treated at 200 °C and 400 °C did not significantly affect the drying shrinkage of the mortar. However, treatment at 600 °C and 800 °C effectively suppressed drying shrinkage. Compared to untreated RCP, RCP treated at 800 °C reduced the drying shrinkage by 7.4% (R3-800-30) to 19.8% (R1-800-20). One of the primary causes of drying shrinkage in cementitious materials is the increased capillary forces due to moisture evaporation. The C_2S formed at high temperatures enhances the reactivity of RCP, promoting mortar hydration and refining the pore structure of the cementitious matrix, thereby strengthening resistance to shrinkage deformation (Sasui et al., 2024).

As the recycling cycle of RCP increases, the drying shrinkage deformation of the mortar also increases. This phenomenon is linked to previous findings that RCP derived from more frequently recycled concrete is more porous and contains more microcracks compared to RCP from concrete recycled fewer times (Kim et al., 2023b). In essence, more frequent recycling reduces stiffness in RCP, which in turn lowers the mortar resistance to shrinkage (Carriço et al., 2022). However, the shrinkage-reducing effect of RCP activated at 600 °C and 800 °C remains consistently evident. Notably, at a replacement rate of 10%, mortar containing RCP3 exhibits lower shrinkage compared to the standard mortar, irrespective of the activation. At a replacement rate of 20%, mortars with RCP1 treated at 600 °C and 800 °C show lower drying shrinkage than the standard mortar, while RCP2 and RCP3 need to be activated at 800 °C to achieve better shrinkage resistance compared to the standard mortar. When the replacement rate increases to 30%, all mortars demonstrate greater shrinkage than the standard mortar.

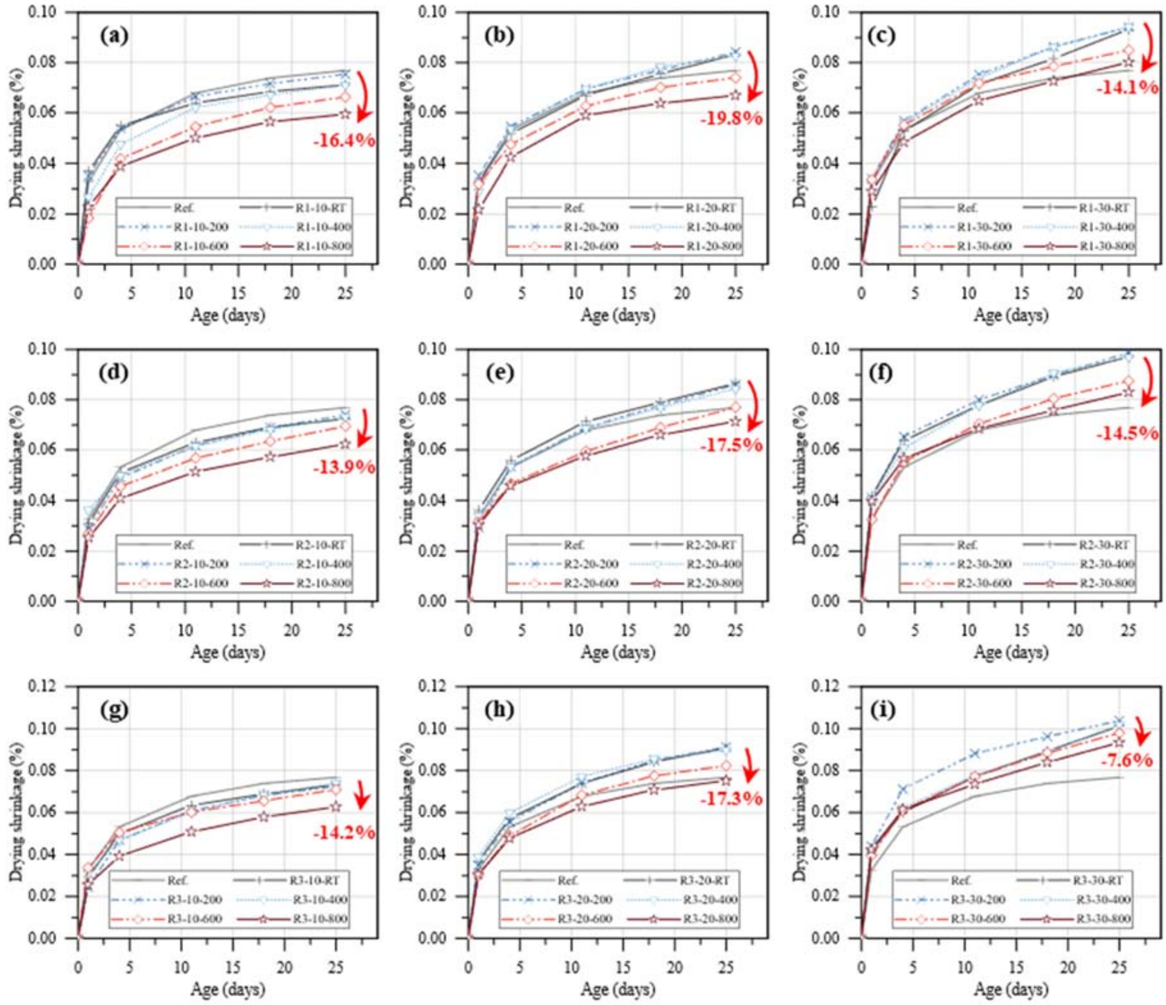

Figure 8. Drying shrinkage of mortar with multi-recycled concrete powders

3.5 Water absorption

The water absorption of mortars at 28 days is shown in Figure 9. The reference mortar had a water absorption of 6.64%, while mortars incorporating RCPs with varying replacement rates and recycling cycles exhibited water absorption ranging from 7.13% to 9.34%.

As expected, the water absorption of mortars with untreated RCPs increased with higher replacement rates. Specifically, the water absorption for samples RCP1-RT-10, RCP1-RT-20, and RCP1-RT-30 was 9.0%, 19.8%, and 37.3% higher compared to the standard mortar. This increase is attributed to the higher porosity and lower reactivity of RCP compared to OPC, resulting in more voids within the specimens (C. Liu et al., 2022). Consistent with previous research (Kim et al., 2023b), RCPs that have undergone more recycling cycles are more porous than those recycled fewer times, leading to higher water absorption of mortar. At replacement rates of 10%, 20%, and 30%, the water absorption of RCP3-based mortars was 8.3%, 3.7%, and 2.5% higher, respectively, compared to RCP1-based mortars.

Activating RCP at high temperatures refines the pore structure of the mixture, which becomes loose due to the incorporation of RCPs, helping to suppress the increase in water absorption. Compared to mortars with untreated RCPs, the use of RCPs heated to 600 °C reduced water absorption by up to 4.2% (R1-600-30), while mortars with RCPs treated at 800 °C decreased water absorption by 6.2% (R1-800-20). Similar to other test results conducted in this study, heat treatment of RCPs at 200 °C and 400 °C did not show a consistent trend in water absorption, with the most significant improvement observed at 800 °C.

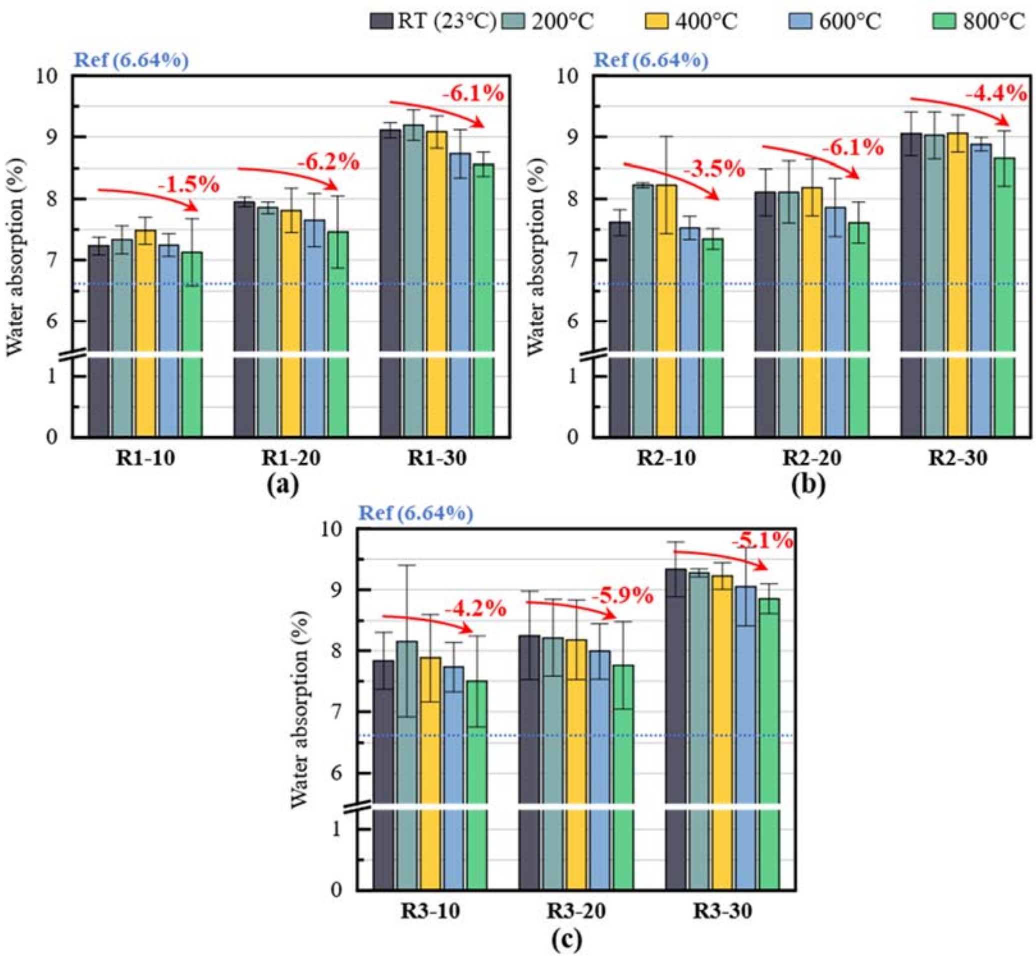

Figure 9. Water absorption of mortar with multi-recycled concrete powders

4. Discussion

Summarizing the experimental results of this study, the performance of cementitious materials containing RCP decreases with an increasing number of recycling cycles and replacement rates. However, thermal activation can partially compensate for this performance reduction. Ultimately, a key issue worth further discussion is whether multi-RCP can be effectively utilized. Based on the 28-day compressive strength of mortars designed according to EN197-1, the cement used in the mixture can be classified into grades 32.5, 42.5, and 52.5. Table 3 presents the grades of mortars prepared in this study with varying recycling cycles, replacement rates, and thermal treatment temperatures. The standard mortar without RCP is classified as grade 52.5. In contrast, mortars containing RCP can downgrade to grade 32.5 with increasing replacement rates and recycling cycles, but thermal activation can maintain them at grade 52.5. Targeting the 42.5 grade, commonly used in general construction, RCP can be utilized without thermal treatment at low replacement rates (i.e., 10%) for up to three times of recycling. However, to achieve an equivalent grade to OPC, thermal treatment at 600 °C and 800 °C is required.

Table 3. Cement grades

	Activation temperature				
	Untreated	**200 °C**	**400 °C**	**600 °C**	**800 °C**
Ref.	**52.5**	Not tested	Not tested	Not tested	Not tested
RCP1-10	**52.5**	**42.5**	**42.5**	**52.5**	**52.5**
RCP1-20	32.5	32.5	32.5	**42.5**	**42.5**
RCP1-30	32.5	32.5	32.5	32.5	32.5
RCP2-10	**42.5**	**42.5**	**42.5**	**52.5**	**52.5**
RCP2-20	32.5	32.5	32.5	32.5	**42.5**
RCP2-30	32.5	32.5	32.5	32.5	32.5
RCP3-10	**42.5**	**42.5**	**42.5**	**42.5**	**52.5**
RCP3-20	32.5	32.5	32.5	32.5	32.5
RCP3-30	Not applicable	Not applicable	Not applicable	32.5	32.5

The unit cost and GWP of 1m³ of concrete when RCP replaces OPC at rates of 10%, 20%, and 30% are shown in Figures 10 (a) and (b), respectively. Using untreated RCP, the production cost of concrete decreases by 6%, 12%, and 18% at these replacement rates, while the GWP decreases by 9%, 17%, and 26%. This reduction is attributed to the decreased amount of cement, which is a major contributor to both high costs and CO_2 emissions in concrete components. As expected, the cost and GWP of concrete containing thermally treated RCP increase due to the thermal energy required for activation, with the highest production cost and GWP observed when RCP is heated to 800 °C. Nonetheless, at a 30% replacement rate, the GWP of RCP-based concrete is still 5-22% lower than that of conventional concrete. This is likely because the thermal activation temperatures (600-800 °C) are significantly lower than the clinker calcination (1450 °C). In terms of production cost, integrating thermally treated RCP was observed to potentially increase the production cost compared to concrete made solely with OPC. For instance, a 10% replacement with 800 °C-activated RCP increased the cost by 1%. Although the production cost can vary significantly due to factors such as the power consumption of the equipment used to heat the RCP, these results align with the International Energy Agency report that that producing low-emission cement is, on average, 75% more expensive than traditional cement production (IEA, 2023).

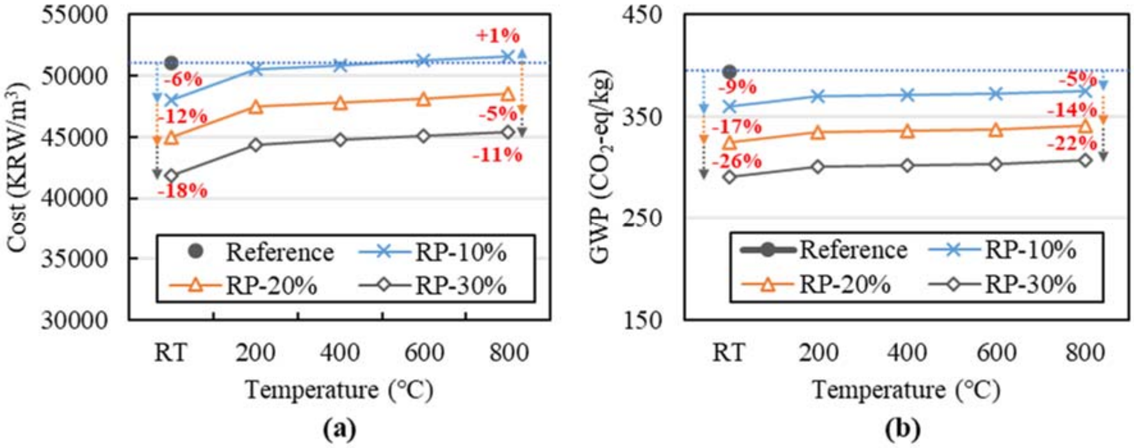

Figure 10. Cost and global warming potential of concrete with recycled concrete powders

Thermal activation can be considered an effective method to modify the characteristics of RCP, contributing to the performance improvement of cementitious materials. However, the unconditional application of thermal activation could lead to resource waste. Ideally, replacing cement with untreated RCP at lower replacement can minimize the loss of mortar properties while maximizing environmental benefits. Accurate statistics on the generation of RCP are not well established. However, some studies suggest that recycling concrete through crushing produces coarse and fine aggregates in a ratio of approximately 6:4 (Nagataki et al., 2004), with about 20% of the fine aggregate consisting of particles smaller than 63 µm (Kalinowska-Wichrowska et al., 2019). This means that from 1 tonne of concrete, approximately 600 kg of coarse aggregate, 320 kg of fine aggregate, and 80 kg of powder can be produced. In 2014, an estimated 3 billion tonnes of construction waste were generated (Akhtar and Sarmah, 2018). If fully recycled, this could yield 240 million tonnes of fine powder, equating to 5.8% of the 4.1 billion tonnes of cement produced in 2021 (Tkachenko et al., 2023). Integrating this amount of RCP into concrete might not necessitate modifications such as thermal activation. In contrast, South Korea generated about 86.44 million tonnes of construction waste in 2020 (ME, 2023). If fully recycled, this could result in approximately 6.9 million tonnes of powder, accounting for about 14.7% of the 47 million tonnes of cement produced in South Korea in the same year (Korea Cement Association, 2021). In such cases, thermal activation could be considered a viable option for utilizing RCP. Therefore, by understanding various factors such as the amount and composition of construction waste and the recycling rate, RCP can be used in a more environmentally friendly and performance-efficient manner.

5. Conclusions

In this study, RCPs generated from the repeated recycling of concrete were collected and used as partial replacements for cement in mortars. The following conclusions were drawn:

- The RCP produced during concrete recycling become more porous with increasing recycling cycles, which negatively effects on the performance of cement-based materials. Specifically, using 30% RCP3 resulted in a 44.3% reduction in compressive strength and a 26.8% reduction in flexural strength compared to standard mortar with no RCP.
- RCP activated at 600°C and 800°C positively influenced the properties of mortars. Specifically, the mortar with 10% 800°C-activated RCP3 showed compressive strength nearly equivalent to that of standard mortar (2.1% lower) and 18.4% lower drying shrinkage, demonstrating the potential of thermal activation for the use of multi-RCP.
- From a performance standpoint, adjusting the replacement rate and applying thermal activation allow multi-recycled RCP to meet the cement grades specified by EN197-1 standards.
- The energy required for RCP activation increased both the production cost and GWP of the concrete. In some cases, such as using 10% 800°C-activated RCP, the production cost was slightly higher than that of OPC-based concrete. However, the GWP of concrete containing 800°C-activated RCP was still 5-22% lower.

Acknowledgment

This research was funded in part by the National Science Centre, Poland (Grant number 2022/45/N/ST8/01782).

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