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From waste to value: Upcycling residual cementitious fines via flash calcination

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ABSTRACT

The concrete industry contributes ~8% of global CO₂ emissions, mainly from clinker production. Recycling concrete yields residual cementitious fines (RCF), enabling clinker substitution. This study investigates flash calcination as a thermal activation route to restore RCF reactivity. RCF were flash calcined (fRCF) and compared with untreated RCF and limestone powder. Chemical, mineralogical and physical analyses were performed. Flash calcination dehydrated portlandite and ettringite, reduced particle size, increased density and enhanced reactivity. Mortars with 25-100% clinker replacement by fRCF were tested in CEM I and CEM III/B at 1, 7, and 28 days. At 100% replacement, fRCF reached 16.3 MPa at 28 days. In CEM III/B, fRCF retained 99.4-101.4% of reference strength at 25-75% replacement, versus 36.9-78.7% in CEM I. Flash calcination thus increases RCF reactivity, enabling high clinker substitution, particularly in slag-containing systems. EU demolition waste can supply 75% clinker replacement in CEM III/B or 46% of total demand.

1. Introduction

Concrete production is one of the most carbon intensive industrial processes globally, accounting for approximately 8% of the total anthropogenic CO₂ emissions with the clinker in cement being the primary contributor (Miller and Moore, 2020; Benhelal et al., 2013). The production of Portland cement clinker requires limestone and clay calcination at temperatures exceeding 1450 °C, resulting in the release of both process related CO₂ from limestone decomposition and energy related emissions from fossil fuel combustion (Benhelal et al., 2013; Barcelo et al., 2014). With global cement production exceeding 4 billion tons annually and projected to increase substantially due to urbanization and infrastructure development, the environmental impact of clinker production presents a critical challenge for achieving climate targets and sustainable construction practices (Miller et al., 2016; Favier et al., 2018; Environment et al., 2018).

Concrete recycling has therefore emerged to not only reduce the use of raw materials, but also reduce CO₂ emissions. With the development of innovative recycling techniques, it is now possible to produce a fine (cementitious) powder fraction containing most of the cement. This was previously thought not achievable, as traditional concrete recycling

produced only two fractions: coarse aggregates (>4 mm) and fine aggregates (0-4 mm). Only a small amount of the coarse aggregates is used in structural concrete, whereas the fine aggregates are not used at all (Fig. 1). Innovative concrete recycling however, has the potential to produce clean secondary aggregates (0.25-4 mm and >4 mm) and residual cementitious fines (RCF; 0-0.065 mm) that can potentially replace the primary materials (Fig. 2) (Alberda van Ekenstein et al., 2024).

The European standard EN 197-6 (Normalisatie-instituut, 2023) permits cement replacement with residual cementitious fines (RCF) in the range of 6-35% by mass, depending on the cement type. Previous studies have demonstrated that untreated RCF can be effectively incorporated into cement mixtures without significant performance degradation within this range. Oksri-Nelfia et al. (2016) found that up to 25% replacement of ordinary Portland cement with RCF maintained comparable mortar properties. Similarly, Topić and Prošek (2017) investigated RCF with an average grain size of 12 µm and observed that 5-15% clinker replacement by RCF actually increased flexural strength (7-25% increase), while 25% replacement still achieved compressive strength comparable to reference samples (4% decrease). The authors attributed these results to the combined micro-filler effect and inherent reactivity of RCF. However, to achieve higher replacement ratios and

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subsequently reduce the environmental impact of concrete, advanced treatment technologies and processes are required to increase the quality and reactivity of RCF. Researchers have explored multiple upcycling methods to activate RCF, with mechanical activation, thermal treatment, carbonation treatment and chemical activation emerging as the most widely adopted approaches in literature (Zhang et al., 2022; Florea et al., 2014; Mehdizadeh et al., 2022; Zajac et al., 2020; Sajedi and Razak, 2011; Rajczakowska et al., 2025).

Thermal treatment has obtained particular interest due to its potential to reverse the hydration process through dehydration. When subjected to increased temperatures, hydrated cement undergoes decomposition of hydration products, which may result in the formation of reactive phases comparable to those found in primary cement. The decomposition of hydration products such as portlandite and calcium silicate hydrate can restore hydraulic reactivity and enable rehydration upon contact with water (Shui et al., 2008, 2009). Conventional thermal treatment using rotary kilns or static ovens has demonstrated the feasibility of this approach. However, these methods are characterized by long processing times, high energy consumption, and formation of unwanted phases during extended heating cycles. Flash calcination presents an innovative alternative that addresses these limitations through rapid, high-temperature processing with residence times measured in seconds to minutes rather than hours (Bridson et al., 1985; Chu et al., 2022; San Nicolas et al., 2013). This technique has been successfully implemented across various industries for processing materials including magnesite ore, limestone, clays, and sediments (Chu et al., 2022; An et al., 2025; Claverie et al., 2015; Teklay et al., 2015; Ying et al., 2000), with clay calcination receiving particular attention for producing pozzolanic cement replacement materials. The process involves rapidly heating material to high temperatures, holding briefly and then rapidly cooling (Teklay et al., 2015; Koutsouradi et al., 2025). This approach offers improved energy efficiency and economic viability compared to conventional longer-duration processes. However, flash calcination has not yet been investigated in concrete recycling as an upcycling technique for the activation of RCF.

The application of flash calcination for the dehydration and reactivation of RCF presents a promising pathway towards more sustainable concrete production. During treatment, hydration products such as portlandite and calcium silicate hydrates present in the fines are effectively dehydrated. The short residence times help minimize the formation of less and non-reactive phases that may develop under prolonged thermal exposure, while the high heating rates can promote the creation of reactive phases. Given that the emerging recycling technologies yield RCF containing substantial quantities of residual cementitious material and considering the demonstrated effectiveness of flash calcination in

other industrial sectors, the systematic investigation of this technique for RCF reactivation is of interest.

To determine the most effective upcycling strategy for RCF, a series of preliminary experiments was carried out to compare four potential treatment methods: mechanical grinding, accelerated carbonation, conventional oven heating and flash calcination (Farchich, 2024). The performance of these treatments was evaluated using mortar specimens with varying clinker replacement ratios (50%, 75%, and 100%) in both CEM I- (ordinary Portland cement; 52.5 R) and CEM III/B- (blast furnace slag cement; composed of 70% ground granulated blast furnace slag and 30% CEM I 52.5 R) based mortars. The 28-day compressive strength results (Fig. 3) demonstrated that flash calcination consistently achieved superior mechanical performance across all replacement ratios and cement types. Based on these comparative results, flash calcination was identified as the most promising treatment approach and was therefore selected for detailed investigation in the present study.

This study therefore provides an in-depth investigation into the potential of flash calcination as an upcycling treatment for RCF produced through an advanced mechanical separation recycling process (Rutte Groep (Producer), 2019; Schenk, 2011). The objectives of the study are threefold: (i) to evaluate the RCF material property changes induced by flash calcination, (ii) to assess the reactivity of the treated fines (fRCF) by means of isothermal calorimetry, and (iii) to determine the mechanical performance of mortars incorporating flash calcined residual cementitious fines (fRCF) as (partial) clinker replacements.

2. Materials and methods

2.1. RCF production

The RCF used in this study were obtained from CEM I-based concrete blocks (Block 1 from (Alberda van Ekenstein et al., 2026)). These blocks (Fig. 4), 5 units with dimensions of 160 x 80 x 80 cm, were specifically cast for this experiment to ensure a controlled and uniform starting material prior to the recycling and fragmentation process.

At the age of approximately 1.5 years, the blocks were therefore initially crushed using a hydraulic excavator to produce concrete rubble suitable for further processing in an impact crusher, which reduced the material to a maximum particle size of approximately 55 mm. This pre-crushed material was subsequently processed using an innovative crusher (the 'Smart Liberator', Urban Mine B.V.) designed to mechanically separate adhered cement stone from the aggregate particles using hardness differences between the cement stone and aggregates. In this process, the cement stone is selectively fragmented while the sand and gravel particles remain largely intact (Rutte Groep (Producer), 2019;

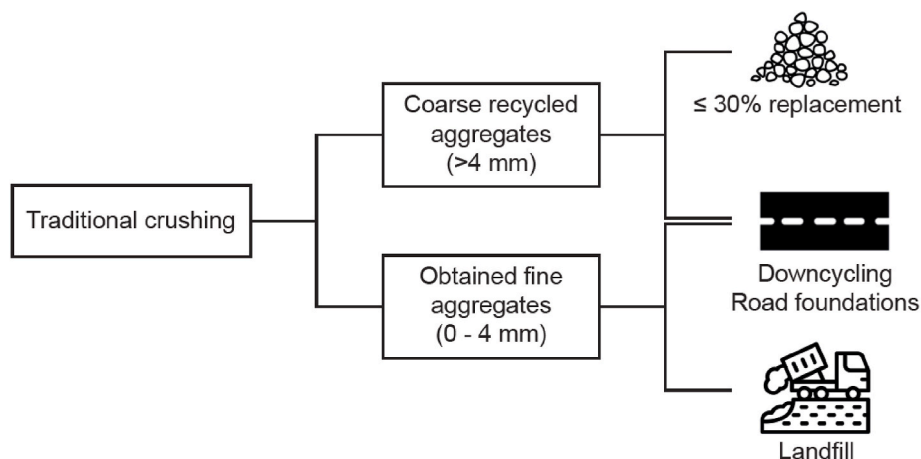


Fig. 1. Traditional recycling and its produced fractions. A small amount of the coarse aggregates (<30%) is used in concrete for structural applications, whereas the fine aggregates are mostly downcycled as road foundations or landfilled.

Schenk, 2011). This treatment produced two output fractions: 0–4 mm and 4–22 mm. The 0–4 mm fraction, which contains the highest concentration of residual cementitious material, was further processed using an air separation system (the ‘Smart Refiner’, Urban Mine B.V.), resulting in three fractions: clean secondary sand (0.25–4 mm) and two fine powder fractions (0–65 μm and 65–250 μm). The 0–65 μm fraction, assumed to contain the majority of the original cementitious binder, was selected for this study and is hereafter referred to as RCF. Fig. 5 shows an overview of the obtained fractions.

2.2. Flash calcination

A custom made lab-scale flash calciner setup (provided by Urban Mine B.V.), as illustrated in Fig. 6, was used for the thermal treatment (flash calcination) of the RCF. The system operates by directing heated air from the heater toward the heating zone. Material is introduced through a feeder mechanism and transported toward a vertical tube by a rotating screw that slowly introduces small amounts of material into the machine. From here the material is carried by the heated airflow into the heating zone for thermal treatment. The material is continuously fed into the heated airflow and transported through the heating zone, where it remains for a few seconds at the high internal process temperature. The current laboratory-scale setup operates at limited processing capacity, with a feed rate of approximately 150 g/h and manual dosing used to keep the feeder filled during operation. The temperature was set to 800 °C, which resulted in a core temperature in the heating zone of 700 – 750 °C. This range was selected based on literature reporting that the highest compressive strength for thermally treated cementitious fines was obtained within this temperature range (Shui et al., 2009, 2014; Xinwei et al., 2010; Vyšvaril et al., 2014; Serpell and Lopez, 2015; Serpell and Zunino, 2017; Xuan and Shui, 2010). After heating, the calcined material passes through a cooling section designed to rapidly reduce its temperature before being collected in a designated container.

2.3. Characterization of fRCF

To evaluate the properties and reactivity of the flash calcined material (fRCF), three sample types were examined and characterized: primary CEM I 52.5R as reference material and RCF and fRCF, both retrieved from the CEM I-based concrete described in Section 2.1. The following sections describe the analytical methods used to characterize these sample types.

2.3.1. Particle size distribution and density

An EyeTech Laser diffractometer was used to determine the particle size distribution of the samples. It uses a liquid cell in which particles are dispersed in a fluid. For this analysis, 500 ml ethanol was used and the samples were added gradually until the diffractometer detected an adequate particle concentration. Ethanol was selected instead of water, because hydraulic particles may react in aqueous environments, which could alter the measured size distribution.

Density of the samples was measured using an Ultrapycometer 5000 instrument, which uses helium gas to determine the volume of the samples. Before these measurements, samples were subjected to a drying process at 105 °C until reaching constant mass to eliminate moisture content in accordance with EN-1097-5 (Normalisatie-instituut, 2008).

2.3.2. Thermogravimetric analysis and differential scanning calorimetry

Thermal analysis was used to gain insight in the effectiveness of the dehydration of fRCF in comparison to primary Portland cement and RCF. Simultaneous thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) measurements were performed on a Netzsch STA 449 F3 Jupiter apparatus. Powder samples were analysed in covered alumina crucibles within an argon atmosphere. The temperature increased with a heating rate of 10 °C/min from 40 to 1000 °C.

2.3.3. X-ray fluorescence

The elemental composition of the samples was determined using X-ray fluorescence spectroscopy. For this analysis, a handheld X-ray fluorescence (HXRF) analyser, the X-MET8000 Expert GEO, was utilized. This instrument features a high-resolution 25 mm² silicon-drift detector coupled with a rhodium target X-ray tube. All measurements were conducted with a consistent spot size of 10.7 × 9.4 mm. Prior to the analysis, powder samples were placed in specialized sample cups and sealed with a transparent thin film (Mylar® thin film: 3.6 μm).

2.3.4. X-ray diffraction

X-ray diffraction (XRD) was used to characterize the crystalline phases in the samples. A Bruker D8 Advance Eco X-ray diffractometer equipped with a LynxEye XE-T detector performed the analysis. A Cu-tube X-ray source generated Cu-K α radiation with a wavelength of 1.5418 Å. The instrument was operated at 40 kV and 25 mA. Samples were scanned across a 2 θ range from 5° to 75°.

2.3.5. Fourier transform infrared spectroscopy

Molecular structural variations among the samples were investigated using Fourier transform infrared spectroscopy (FTIR). The spectral analysis was conducted with a Nicolet iS50 spectrometer in the 400–4000 cm^{−1} range. Each measurement involved 24 scans at a 4 cm^{−1} resolution. Powdered samples were positioned on the instrument's crystal and compressed using the pressure anvil.

2.3.6. Isothermal calorimetry

Isothermal calorimetry was used to assess whether flash calcination successfully restored reactivity to the RCF. By comparing RCF with fRCF insight is gained on powder reactivity. An increase in heat release of fRCF compared to RCF would indicate effective upcycling (restore hydraulic reactivity) of RCF and indicate potential for cement replacement.

Cement reactivity and pozzolanic reactivity were assessed using an isothermal conduction calorimetry with a TAM Air instrument by Heidelberg Materials Benelux following EN 196-11 (Normalisatie-instituut, 2019) and EN 196-12 (Normalisatie-instituut, 2024), respectively. For

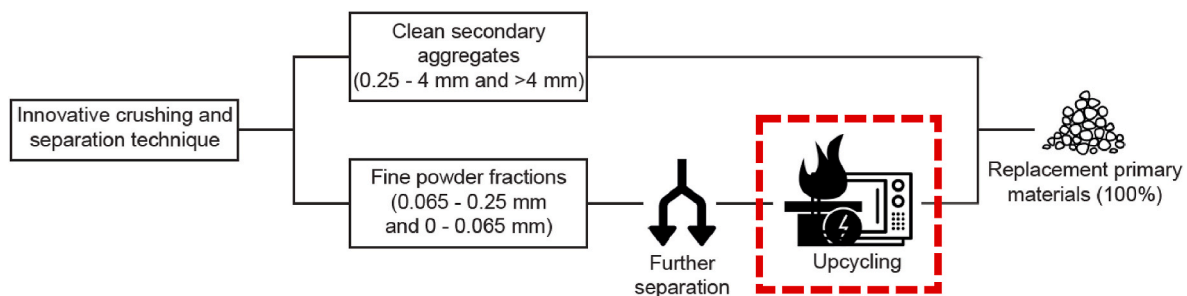


Fig. 2. Innovative recycling and its produced fractions. The clean secondary aggregates can directly be used in (structural) concrete, whereas the fine powder fractions, of which 0 – 0.065 mm is referred to in this study as residual cementitious fines (RCF), can be further separated and upcycled before application.

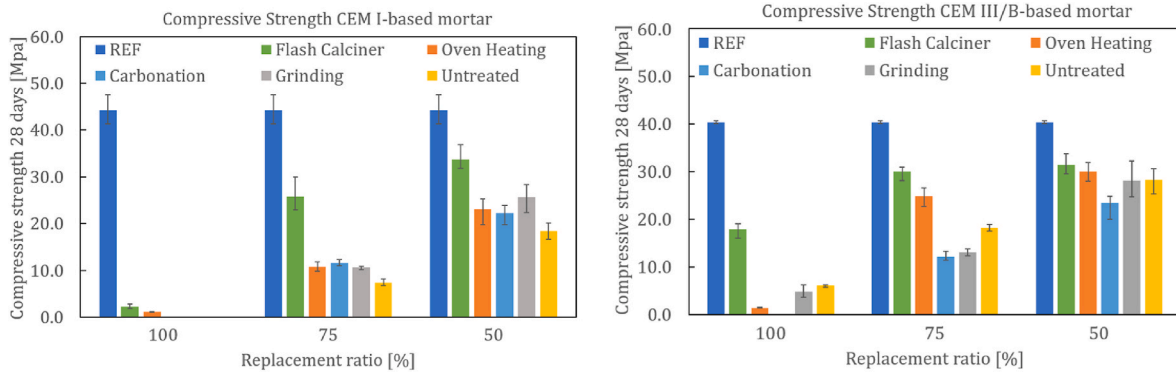


Fig. 3. Compressive strength after 28 days of CEM I- and CEM III/B-based mortars for clinker replacement ratios of 50%, 75% and 100%. Mortar prisms with flash calcined RCF achieved the highest strength for all tests. Adapted from (Farchich, 2024).



Fig. 4. CEM I-based concrete blocks produced for this experiment. In total 5 units were cast and stored outdoors for approximately 1.5 years.

cement reactivity (EN 196-11 (Normalisatie-instituut, 2019)), heat flow was determined at 20 °C using paste mixtures prepared via the external mixing method: 4 g of paste were produced by combining cementitious powder (the three samples plus a commercially available CEM III/B 42.5 N) and water (water-to-cement ratio: 0.4) in ampoules, mixing at

full speed with a Vortex mixer and placing them in the instrument within 4 min of water addition. For pozzolanic reactivity (EN 196-12 (Normalisatie-instituut, 2024)), measurements were conducted at 40 °C using components mixed in ampoules at a mass ratio of cementitious fines:Ca(OH)₂:CaCO₃:potassium solution (K-solution: 4.0 g KOH and 20 g K₂SO₄ in 1.0 L) = 1.0:3.0:0.50:5.40, with specific quantities of 1.0 g cementitious fines (RCF, fRCF, CEM III/B 42.5 N, but not CEM I as this is a non-pozzolanic material), 3.0 g Ca(OH)₂, 0.50 g CaCO₃, and 5.40 g (is 5.4 ml) K-solution. Solid components were mixed for 1 min using a Vortex mixer, both sample ampoule and K-solution were pre-conditioned at 40 °C before combining. Then the reaction was initiated by adding the K-solution followed by 2 min of mixing at full speed. Both measurement series ran for 7 days (168 h).

2.4. Functional performance assessment

To evaluate the potential of fRCF to function as a binder, activator of pozzolanic materials or as a filler, parallel mixtures were produced using RCF and limestone powder (LS, assumed to act as inert filler) as clinker substitution materials at identical substitution levels. This approach enables a direct assessment of the effectiveness of the thermal activation process. An overview of the mortar compositions is provided in Table 1. The compressive strength of the produced mortar prisms were measured in accordance with EN 196-1 (Normalisatie-instituut, 2016). Mortar mixtures were produced to study the impact of (partial) clinker replacement by fRCF on the strength development of CEM I and CEM III/B based mortars. Throughout this study, clinker replacement in the mortar mixtures refers to the replacement of CEM I, irrespective of the cement type used. The clinker component within these mortar mixtures was systematically replaced with fRCF at volumetric substitution rates of 25%, 50%, 75% and 100%. All replacements were conducted on a volume-equivalent basis rather than by mass, ensuring consistent total



Fig. 5. Fractions obtained through the innovative crushing and separation process. From left to right: secondary gravel, secondary sand, coarse fines 65-250 µm and RCF 0-65 µm.

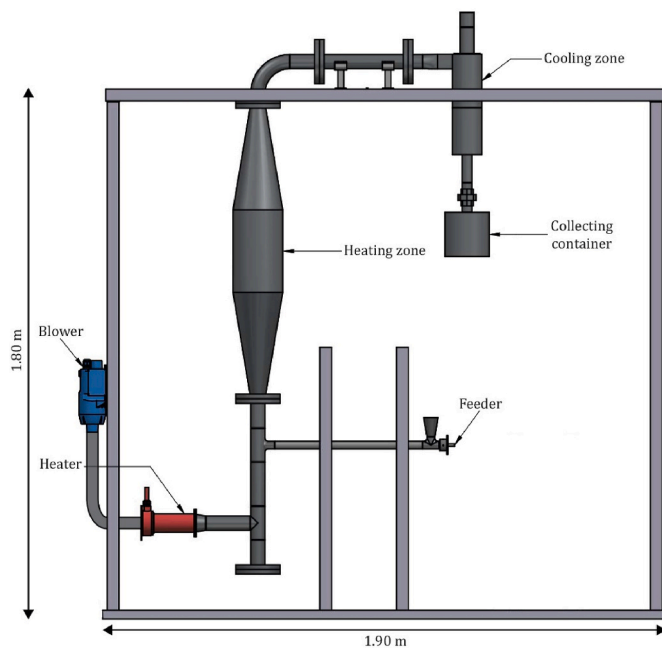


Fig. 6. Schematic overview of the laboratory scale Flash Calciner setup. RCF is introduced through a feeder and transported to the heating zone, where heated air treats the material before it moves through the cooling zone to the collecting container.

binder volume across all mixtures. To maintain adequate workability while keeping the water-to-cement constant across all mixtures, a plasticizer (CUGLA HR con. 35% SPL) was added only where the workability was visibly reduced, specifically for fRCF₇₅ and fRCF₁₀₀ CEM I-based mortars. No plasticizer was added to the other mixtures, as they showed no noticeable reduction in workability.

The raw materials were mixed with a Hobart mixer according to EN 196-1 (Normalisatie-instituut, 2016). Samples were demoulded after

24 h and placed in a fog room at 20 °C and 99% relative humidity without sealing. The compressive strength was assessed at 1, 7, and 28 days of curing using a Matest E161N cement compression machine 250 kN, servo plus evolution. For each age, six specimens were tested.

3. Results

3.1. Characterization of fRCF

3.1.1. Particle size distribution, density and x-ray fluorescence

Fig. 7 shows the particle size distribution of primary Portland cement (CEM I), RCF and fRCF. The $d(50)$, representing the median particle size where 50% of the particles are smaller and 50% are larger than the presented size, is 48.67 μm for RCF, 36.72 μm for fRCF and 19.12 μm for CEM I. Both RCF and fRCF consist of coarser particles compared to CEM I. Additionally, the particle size distribution of fRCF indicates that due to the flash calcination treatment its particle size decreased in comparison to the untreated RCF.

The change in density as a result of the flash calcination treatment is shown in Table 2. Additionally, an overview of the chemical composition of CEM I, RCF and fRCF is presented in Table 3. From these results it follows that an increase in density occurred due to flash calcination. The density of RCF, which was the lowest, increased from 2.33 g/cm^3 to 2.68 g/cm^3 (fRCF) after the treatment. However, this is still lower than the density of primary Portland cement (3.07 g/cm^3). Chemical characterization furthermore showed that the composition of RCF and fRCF varies from CEM I. Especially, SiO_2 and CaO show large differences, with SiO_2 content in RCF nearly twice as high and CaO nearly half that of CEM I. Between RCF and fRCF small deviations in chemical composition is also observed. However, observed trends in relative abundance between oxides remain comparable.

3.1.2. Thermogravimetric analysis and differential scanning calorimetry

The TGA and DTG curves for primary Portland cement (CEM I), RCF and fRCF are shown in Fig. 8. The curves show the ranges of dehydration and decarbonation products. RCF is the material with the largest total mass loss (19.4%) between 40 and 1000 °C, whereas fRCF (4.7%) and

Table 1
Mortar mixture design for 3 prisms.

Mortar type	Mix type	Clinker replacement ratio [%]	CEM I 52.5 R [g]	RCF [g]	fRCF [g]	Limestone powder [g]	Ground granulated blast furnace slag [g]	Sand [g]	Water [g]	Plasticizer [g]
CEM I based mortar	REF (CEM I)	0	450	-	-	-	-	1350	225	0
	RCF	25	337.5	85.5	-	-	-	-	-	0
		50	225	171.1	-	-	-	-	-	0
		75	112.5	256.6	-	-	-	-	-	0
		100	0	342.2	-	-	-	-	-	0
	fRCF	25	337.5	-	98.2	-	-	-	-	0
		50	225	-	196.4	-	-	-	-	0
		75	112.5	-	294.6	-	-	-	-	2
		100	0	-	392.8	-	-	-	-	10.3
	LS	25	337.5	-	-	99.0	-	-	-	0
		50	225	-	-	198.1	-	-	-	0
		75	112.5	-	-	297.1	-	-	-	0
		100	0	-	-	396.2	-	-	-	0
CEM III/B based mortar	REF (CEM III/B)	0	135	-	-	-	315	1350	225	0
	RCF	25	101.3	25.7	-	-	-	-	-	0
		50	67.5	51.3	-	-	-	-	-	0
		75	33.8	77.0	-	-	-	-	-	0
		100	0	102.6	-	-	-	-	-	0
	fRCF	25	101.3	-	29.5	-	-	-	-	0
		50	67.5	-	58.9	-	-	-	-	0
		75	33.8	-	88.4	-	-	-	-	0
		100	0	-	117.8	-	-	-	-	0
	LS	25	101.3	-	-	29.7	-	-	-	0
		50	67.5	-	-	59.4	-	-	-	0
		75	33.8	-	-	89.1	-	-	-	0
		100	0	-	-	118.8	-	-	-	0

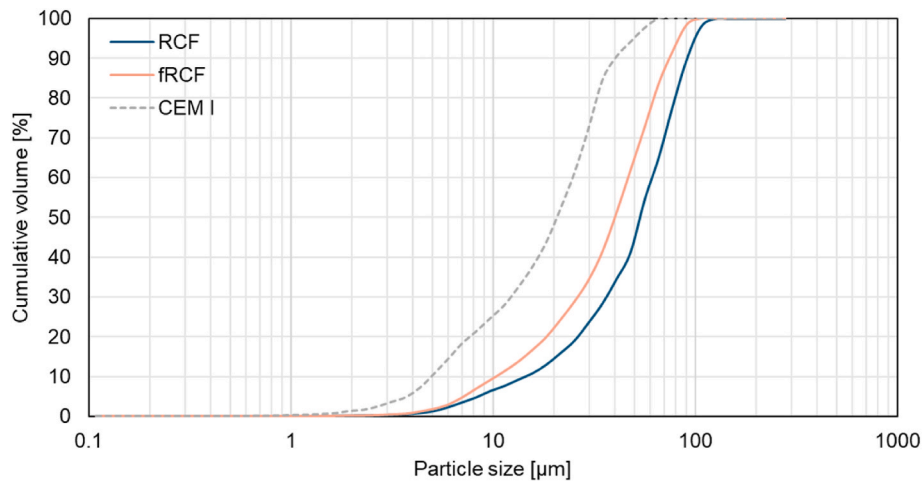


Fig. 7. Particle size distribution of primary Portland cement (CEM I), RCF and fRCF.

Table 2

Density and particle size parameters D(10), D(50) and D(90) of primary Portland cement (CEM I), RCF and fRCF.

	Density [g/cm ³]	D(10) [μm]	D(50) [μm]	D(90) [μm]
RCF	2.33	13.42	48.67	84.78
fRCF	2.68	9.46	36.72	69.06
CEM I	3.07	4.57	19.12	36.68

CEM I (2.8%) have a more comparable mass loss. The DTG curve of RCF displayed three distinct peaks between 40 and 200 °C, corresponding to the evaporation of free water and the dehydration of hydration products

such as ettringite, monosulfate and calcium silicate hydrate (C-S-H) (Alarcon-Ruiz et al., 2005; Bogas et al., 2020). Between 200 and 400 °C, a gradual weight loss occurred as C-S-H, calcium aluminate hydrates and other minor hydrates dehydrate (Marsh and Day, 1988; Alonso and Fernandez, 2004). A second abrupt weight loss was observed at approximately 400 – 500 °C as a result of the decomposition of portlandite (Ca(OH)₂; CH) (Alarcon-Ruiz et al., 2005; Hager, 2013). Between 500 and 700 °C, further gradual dehydration of residual hydrates took place (Marsh and Day, 1988; Alonso and Fernandez, 2004), followed by a minor peak at 700 – 800 °C indicating the decarbonation of calcite (CaCO₃) (Alarcon-Ruiz et al., 2005). Both fRCF and CEM I exhibited comparable mass loss patterns in the ranges of 400 – 500 °C

Table 3

Chemical oxide composition of primary Portland cement (CEM I), RCF and fRCF.

	SiO ₂	Al ₂ O ₃	SO ₃	CaO	K ₂ O	Fe ₂ O ₃	P ₂ O ₅	MgO	TiO ₂	Cl	MnO	SrO
RCF	45.09	6.59	3.08	38.27	1.52	3.07	0.54	0.99	0.32	0.24	0.11	0.18
fRCF	47.40	7.04	3.20	35.40	1.44	2.84	0.49	1.42	0.30	0.21	0.11	0.16
CEM I	21.61	5.12	6.49	62.09	1.19	1.90	0.22	0.66	0.21	0.10	0.10	0.31

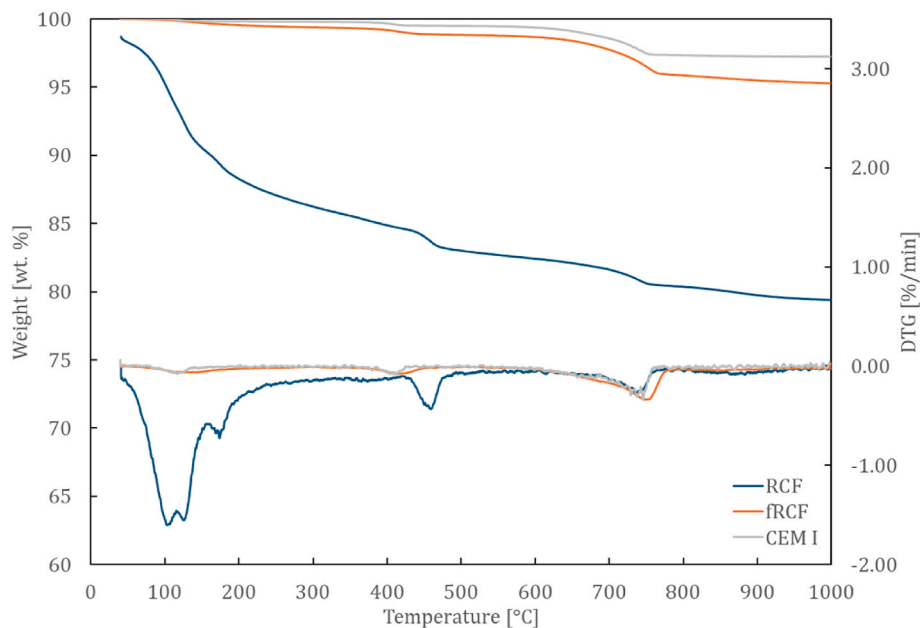


Fig. 8. TGA and DTG curves of RCF and fRCF and primary Portland cement (CEM I). fRCF is comparable to CEM I and shows significantly less mass loss compared to RCF.

and 700 – 800 °C. The mass loss resulting from portlandite decomposition was significantly reduced in both fRCF and CEM I compared to RCF, while the mass loss associated with calcite decomposition was proportionally larger. Other mass loss observed for RCF did not occur in fRCF and CEM I or was significantly reduced.

Fig. 9 shows the DSC curves of primary Portland cement (CEM I), RCF and fRCF. Endothermic peaks observed for RCF correspond to the dehydration processes observed in both TGA and DTG. This is also the case for the CEM I and fRCF curves, which showed minimal endothermic activity. Both RCF and fRCF also reveal a small endothermic peak around 570 °C as a result of the transformation of α -quartz to β -quartz (Florea et al., 2014), which is not present in CEM I.

3.1.3. X-ray diffraction

The X-ray diffraction patterns of primary Portland cement (CEM I), RCF and fRCF are presented in Fig. 10. Based on these patterns, the change in mineralogical composition as a result of the flash calcination treatment were investigated. The primary Portland cement (CEM I) exhibited the characteristic diffraction pattern of fresh cement, with prominent peaks corresponding to the main clinker phases: tricalcium silicate (C_3S), dicalcium silicate (C_2S) and tricalcium aluminate (C_3A). Additional peaks corresponding to tetracalcium aluminoferrite (C_4AF) and gypsum were also observed. Notably, the CEM I pattern showed no quartz peaks, indicating the absence of siliceous aggregate fines. In contrast, both the patterns of RCF and fRCF showed clear quartz peaks, demonstrating the presence of siliceous aggregate fines in these samples. Besides the quartz peaks, the RCF sample exhibited calcite peaks and peaks related to cement hydration products, such as portlandite and ettringite. Following flash calcination, the fRCF sample showed that peaks related to cement hydration products, specifically portlandite and ettringite, are no longer present. Importantly, the fRCF pattern revealed the formation of belite (C_2S) peaks and free lime (CaO) peaks. The quartz peaks remained unchanged in fRCF. Compared to CEM I, not all the initial clinker phases were recovered, but the formation of belite and CaO suggest enhanced cementitious potential compared to the RCF.

3.1.4. Fourier transform infrared spectroscopy

To characterize the chemical composition and phase assemblages of RCF, fRCF and primary Portland cement (CEM I), FTIR spectroscopy was performed on these samples. The spectra are presented in Fig. 11. The FTIR spectra can be divided into several major regions:

- Water region
- Carbonate region
- Silicate region (Kim et al., 2023; Ylmén et al., 2009)

A small band for RCF can be observed in the water region between 3200 and 3400 cm^{-1} , characteristic of O-H stretching vibrations from H_2O (Kim et al., 2023; Ylmén et al., 2009). This band was not observed for the other two samples. Additionally, differences were observed in the carbonate region, providing insights into carbonation history and crystallinity. CEM I exhibited a characteristic peak around 1443 cm^{-1} . In contrast, both RCF and fRCF showed peaks shifted to 1416 cm^{-1} with more pointed peak shapes, indicating a change in $CaCO_3$ structure. The presence of calcite in all samples was confirmed by the characteristic in-plane bending vibration at 714 and 877 cm^{-1} (Chen et al., 2019; Hidalgo et al., 2008). The silicate region showed complex overlapping bands revealing the diverse silicate environments in each sample. Major peaks were identified at 1095 cm^{-1} and 1168 cm^{-1} , attributed to asymmetric Si-O stretching vibrations from multiple sources including quartz aggregate, C-S-H gel, and unreacted cement phases. Both RCF and fRCF show peaks associated with quartz around 696 cm^{-1} , 780 – 800 cm^{-1} and 1095 cm^{-1} , which were not observed in the CEM I spectra (Li et al., 2023). Around 957 cm^{-1} a shift was observed when comparing RCF and fRCF, corresponding to the asymmetric stretching vibrations of Si-O bonds in C-S-H gel (Skocek et al., 2020; Zajac et al., 2023; Ashraf and Olek, 2016), but complex bands in the 900 – 995 cm^{-1} are also associated with the structure of alite and belite (Krol et al., 2022; Fernández-Carrasco et al., 2012). This shift indicates that flash calcination induced structural reorganization of the C-S-H gel, leading to modified silicate polymerization degrees and changes in Ca/Si ratios. Additionally, the shift can be associated with the formation of belite as found by XRD analysis.

3.1.5. Isothermal calorimetry

Fig. 12 and Fig. 13 present the heat flow and cumulative heat release of primary Portland cement (CEM I 52.5R; only in Fig. 12), blast furnace cement (CEM III/B 42.5N), RCF and fRCF pastes in accordance with EN 196-11 and EN 196-12, respectively. Fig. 12 shows that fRCF exhibits the highest cumulative heat release during the initial 6-h period. Beyond this point, CEM I surpasses fRCF in heat release, while fRCF continues to generate more heat than CEM III/B for the first 16 h of the observation period. RCF showed the lowest overall cumulative heat release. However, during the first hour the cumulative heat release was comparable

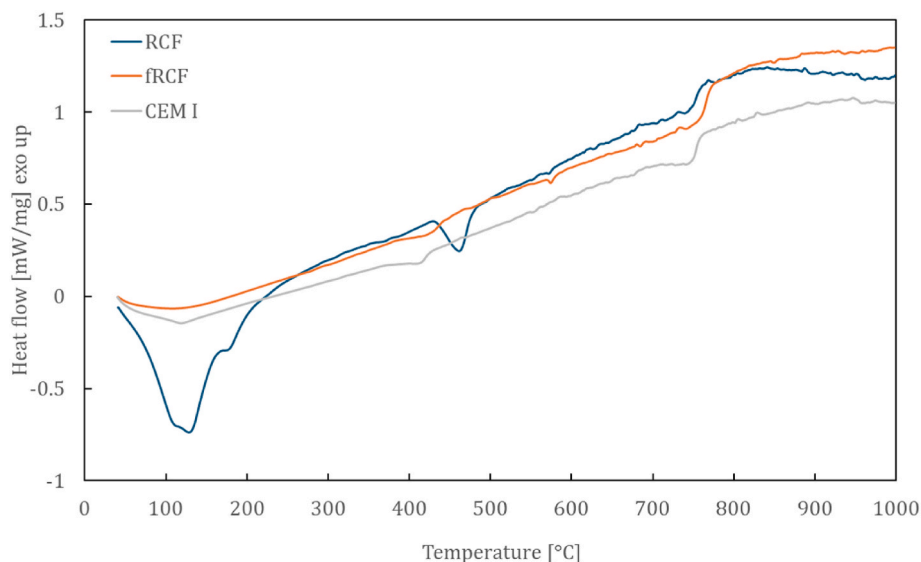


Fig. 9. DSC curves of RCF and fRCF and primary Portland cement (CEM I). Results are complementary to the TGA and DTG results, showing minimal peaks for fRCF and CEM I in comparison to RCF.

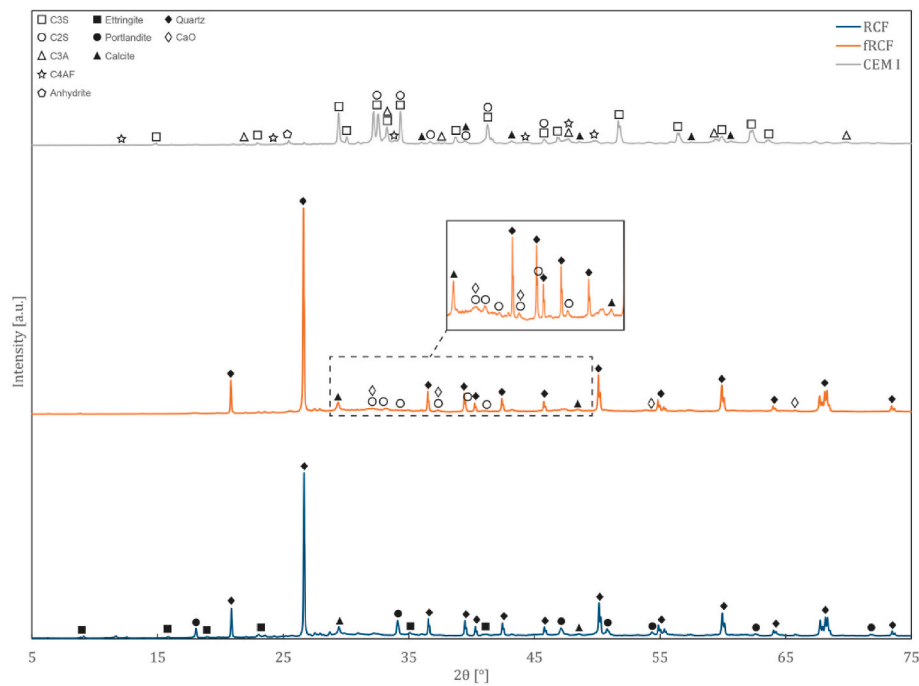


Fig. 10. Diffraction pattern of primary Portland cement (CEM I), fRCF and RCF. The diffraction pattern of fRCF shows that the hydration products are dehydrated and belite (C2S) has formed.

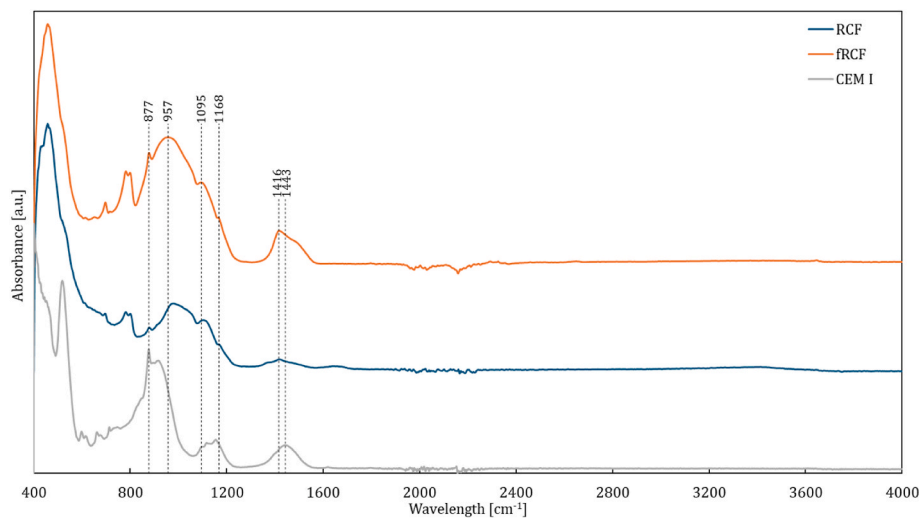


Fig. 11. Normalized FTIR spectra of primary Portland cement (CEM I), RCF and fRCF. Shifts in the absorption bands between the RCF and fRCF spectra indicate molecular structural modifications occurred during flash calcination.

to that of CEM I and for 6 h it was higher than that of CEM III/B. Considering the heat flow, it can be observed that it is mostly generated within the first 2 h for fRCF and in the first 15 min for RCF (first peak). The second peak in the graph is only present for CEM I and CEM III/B and is not observed for RCF and fRCF.

In contrast, Fig. 13 illustrates reactivity response with a focus on supplementary cementitious materials (SCMs). In this case, RCF and fRCF are studied as possible SCMs instead of hydraulic binder. Both the heat flow and cumulative heat release are highest for CEM III/B across the full measurement period followed by fRCF. The RCF has the lowest heat flow and cumulative heat release. Additionally, for both CEM III/B and fRCF a second peak is observed, which is not observed for RCF.

3.2. Functional performance

To gain insight into the mechanical performance and changes in reactivity as a result of the flash calcination treatment, the compressive strength was analysed. Compressive strength results and strength activity index for both CEM I and CEM III/B based mortars across different clinker replacement ratios (0%, 25%, 50%, 75% and 100%) are presented for 1, 7 and 28 days in Fig. 14 and Table 4. RCF, limestone powder (LS) and fRCF were evaluated as replacement materials for the clinker in both cement types, in which LS was hypothesized to act as inert filler.

For CEM I the reference mix (RCF_0, LS_0, fRCF_0, thus no replacement percentage) achieved the highest strength across all ages, with strengths reaching 26.0 MPa and 52.4 MPa at 1 and 28 days, respectively. The replacement of clinker in Portland cement with any of the

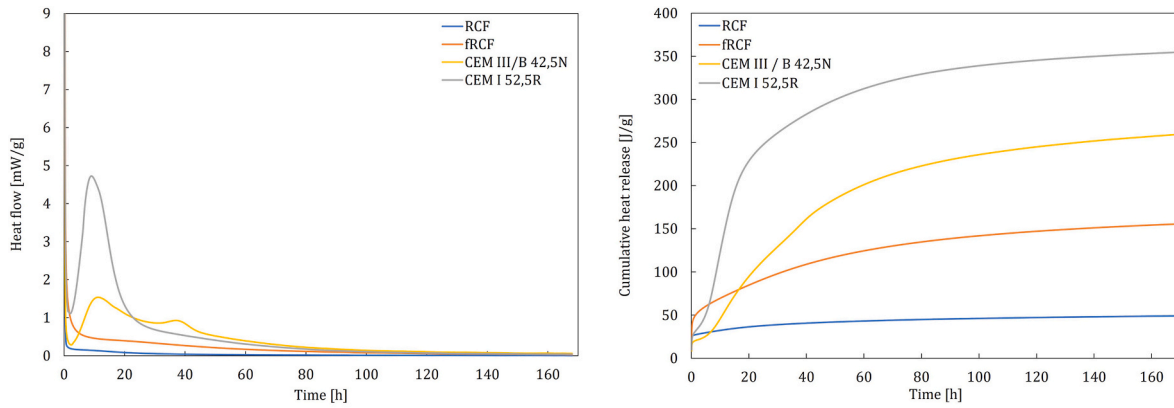


Fig. 12. Heat flow (left) and cumulative heat release (right) in accordance to EN 196-11 (Normalisatie-instituut, 2019).

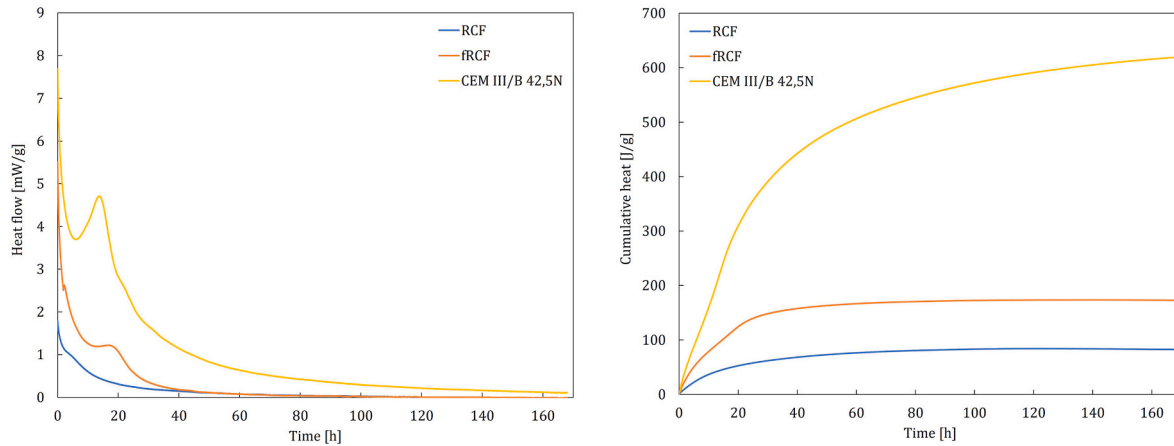


Fig. 13. Heat flow (left) and cumulative heat release (right) in accordance to EN 196-12 (Normalisatie-instituut, 2024).

finer resulted in a reduction of the early age (1 day) strength compared to the reference. The reduction in early age strength was most pronounced with increasing replacement levels of RCF, where mixes $\geq 50\%$ substitution developed strengths below 5.0 MPa (18.5% strength retained) and 15.0 MPa (28.1% strength retained) at 1 and 28 days, respectively. Both LS and fRCF containing mixtures demonstrated higher strength retention than RCF, with the fRCF mixtures outperforming both the RCF and LS mixtures for every age, achieving a strength at 28 days of 41.3 MPa, 33.0 MPa, 19.4 MPa and 16.3 MPa (corresponding to strength retentions of 78.7%, 63.0%, 36.9%, and 31.1% relative to the reference mixture) for the 25%, 50%, 75% and 100% replacement ratios, respectively. At 100% replacement both RCF and LS did not obtain any measurable strength at all ages.

In the CEM III/B mortars, the early age (1 day) strength also reduced for increased clinker replacement levels. The reference mix (RCF₀, LS₀, fRCF₀) achieved a strength of 12.1 MPa and 46.4 MPa at 1 and 28 days, respectively. The early age strength reduction was less pronounced compared to the CEM I mortars except for the 100% replacement level. Between 7 and 28 days the strength development continued steadily with significant gains across all replacement levels. Unlike CEM I mortars, the performance of LS and fRCF at 7 and 28 days was comparable or better than that of the reference mortars for replacement levels of 25%, 50% and 75% with fRCF achieving the best results for higher replacement ratios. The fRCF mortars retained 106.6%, 108.6%, and 102.2% of the reference strength at 7 days and 101.4%, 99.4%, and 100.7% at 28 days for these replacement levels, respectively. RCF also showed less strength reduction for CEM III/B mortars compared to CEM I, but the overall performance for all replacement ratios and ages was lower than that of LS and fRCF except for 100% replacement. LS did not show any

measurable strength at 100% replacement of the clinker part, whereas RCF showed continued strength development reaching 11.7 MPa at 28 days. Interestingly, at 25% replacement LS obtained the highest compressive strength at 7 and 28 days. Overall, the strength development in CEM III/B mortars differs from CEM I mortars. In CEM I systems, fRCF significantly outperforms both RCF and LS, while LS shows better performance than RCF. In CEM III/B systems, however, RCF act as an activator for the slag, particularly evident at 100% clinker replacement. fRCF performs even better, combining slag activation with its own enhanced reactivity. In contrast, the inert LS cannot activate the slag, limiting its performance beyond 75% clinker replacement.

4. Discussion

Based on the results shown in this study, the potential of flash calcination as an upcycling treatment for residual cementitious fines was evaluated through material characterization and mechanical performance assessment. The research aimed to determine the functional role of RCF and fRCF in mortar systems, whether they function as a binder, filler or activator. To investigate this, mechanical performance tests were conducted using two different cement types: CEM I (Portland cement) and CEM III/B (blast furnace slag cement). The inclusion of CEM III/B was particularly relevant as this system requires activation of the latent hydraulic slag component, allowing evaluation of potential activating properties of RCF and fRCF. To distinguish between filler and binder functionality, limestone powder (LS) was included as a reference material, operating under the assumption that LS is chemically inert and contributes primarily through physical filler effects rather than chemical reactions.

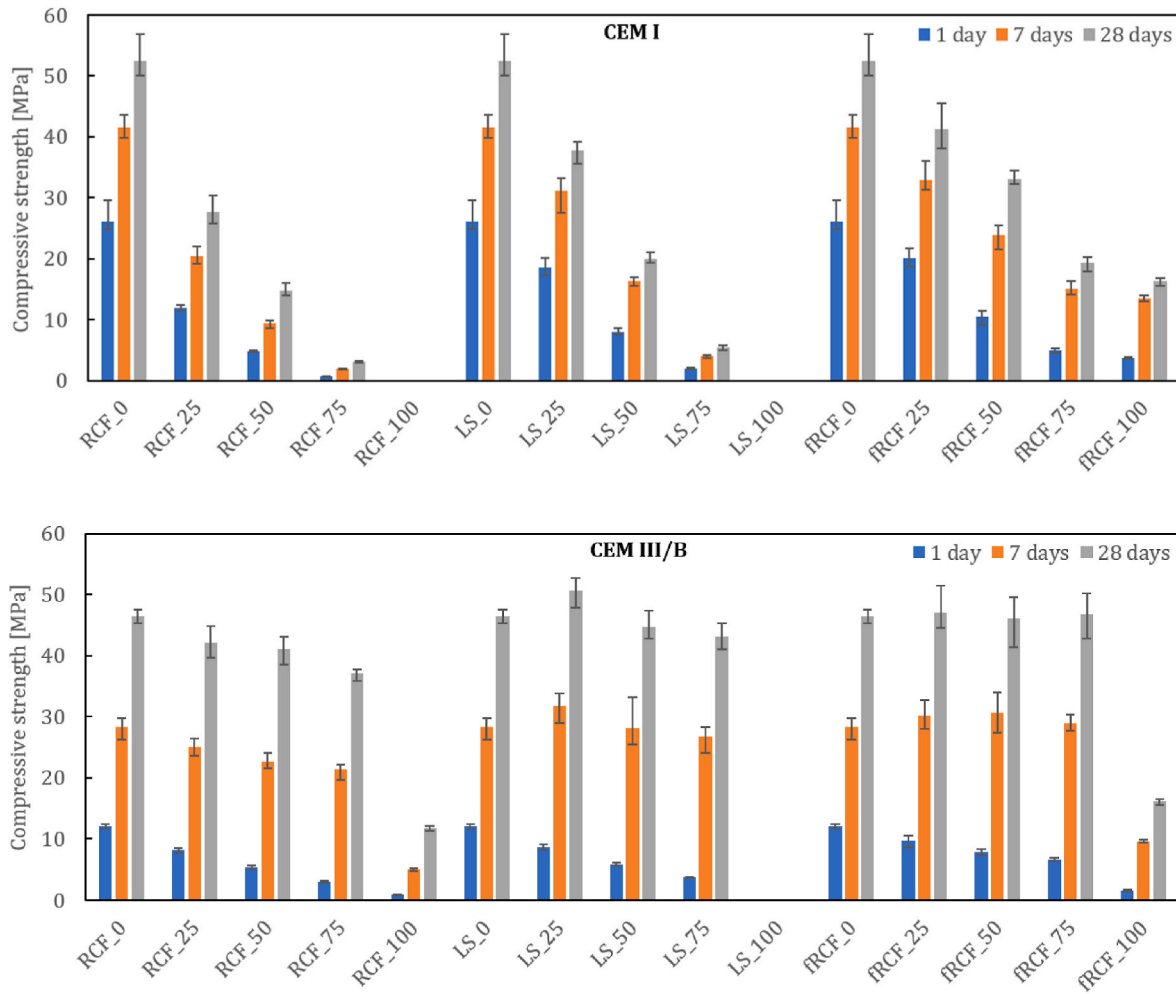


Fig. 14. Development of compressive strength in CEM I- and CEM III/B-based mortar for various replacement ratios. Portland cement is replaced with RCF, limestone powder (LS) and fRCF at volume replacement ratios of 25%, 50%, 75% and 100% in both mortars. In CEM I mortars, LS outperformed RCF, while fRCF outperformed LS. For CEM III/B mortars, LS also achieved better results than RCF, except for 100% clinker replacement. Notably, fRCF demonstrated compressive strength equal to or exceeding LS, especially for 100% clinker replacement.

Table 4

Strength activity index in CEM I- and CEM III/B-based mortars for various replacement ratios. The strength activity index is expressed relative to the corresponding reference mortar, with RCF_0, LS_0 and fRCF_0 representing the respective reference mortars without replacement. Notably, fRCF showed a higher activity index than RCF.

	CEM I			CEM III/B		
	1 day	7 days	28 days	1 day	7 days	28 days
RCF_0	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
RCF_25	45.6%	49.3%	52.9%	67.2%	88.4%	91.0%
RCF_50	18.5%	22.6%	28.1%	43.9%	80.1%	88.6%
RCF_75	2.9%	4.7%	5.9%	25.1%	75.4%	80.0%
RCF_100	0.0%	0.0%	0.0%	7.6%	17.6%	25.3%
LS_0	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
LS_25	71.1%	74.9%	72.2%	71.3%	112.2%	109.1%
LS_50	30.3%	39.2%	38.0%	48.8%	99.7%	96.3%
LS_75	7.5%	9.7%	10.4%	30.9%	94.4%	93.0%
LS_100	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
fRCF_0	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
fRCF_25	77.0%	79.3%	78.7%	80.8%	106.6%	101.4%
fRCF_50	40.5%	57.6%	63.0%	64.9%	108.6%	99.4%
fRCF_75	19.1%	36.3%	36.9%	54.7%	102.2%	100.7%
fRCF_100	14.3%	32.4%	31.1%	13.1%	34.0%	35.1%

4.1. Functional performance and upcycling potential

The compressive strength results revealed distinct performance patterns that varied depending on the cement system used. In CEM I systems, mortars containing untreated RCF consistently showed lower compressive strengths than those containing LS at comparable replacement levels. This indicates that, in this system, potential reactive phases in RCF do not effectively contribute as a binder and have a lower performance than an inert filler (LS). The better performance of LS can be attributed to physical effects such as optimized particle packing and the provision of heterogeneous nucleation sites for cement hydration reactions, which result in a denser microstructure and promote the formation of hydration products (Siddique and Gupta, 2022; Wang et al., 2018a; Moon et al., 2017). In contrast, fRCF consistently outperformed both RCF and LS across all replacement ratios and ages, demonstrating enhanced binding capacity. This improved performance indicates that the flash calcination treatment successfully transformed RCF from a material with limited reactivity into one with significant binding potential, generating reactive phases capable of contributing to strength development through hydraulic reactions. According to EN 197-6 (Normalisatie-instituut, 2023), replacement levels up to 35% RCF are permissible, meaning the RCF_25 values in CEM I mortar meet regulatory requirements despite showing reduced strength compared to the reference. When comparing performance across replacement levels, the

compressive strength of fRCF₅₀ exceeds that of the normatively acceptable RCF₂₅, demonstrating that flash calcination enables higher replacement ratios while maintaining performance above the minimum threshold established for untreated RCF.

The CEM III/B system exhibited different behaviour. RCF showed substantially improved performance compared to its behaviour in CEM I mortars, particularly at higher replacement levels. This improvement suggests an activating effect on the blast furnace slag, which can be attributed to the alkaline nature of RCF and its residual calcium hydroxide content. LS also demonstrated enhanced performance in the CEM III/B system compared to CEM I (except for 100% clinker replacement), which can be attributed to the provision of nucleation sites for enhanced clinker hydration, while the dilution effect and lower aluminium concentration promote slag hydration (Tan et al., 2013; Adu-Amankwah et al., 2017). Notably, fRCF exhibited the most pronounced improvement, with replacement levels of 25%, 50%, and 75% achieving compressive strengths comparable to or exceeding the reference mortar at 7 and 28 days. The improved performance of fRCF can be associated with various mechanisms: the rehydration of dehydrated phases, increased lime content and the formation of additional nucleation sites that facilitate hydration reactions (Florea et al., 2014). The nucleation effect may be particularly beneficial in slag-containing systems due to the typically slower reaction kinetics of slag compared to clinker, where additional nucleation sites can accelerate the overall hydration process and improve long-term strength gain. The enhanced performance of fRCF compared to RCF, observed across both cement systems, aligns with the findings of Carriço et al. (Carriço et al., 2020), who examined thermally treated cement pastes and observed higher compressive strengths compared to untreated materials.

The enhanced reactivity of fRCF was confirmed by the isothermal calorimetry (ICC) results. Following both EN 196-11 (cement reactivity) (Normalisatie-instituut, 2019) and EN 196-12 (pozzolanic reactivity) (Normalisatie-instituut, 2024) methods, fRCF exhibited significantly higher cumulative heat release compared to RCF. For cement reactivity (EN 196-11), fRCF showed the highest heat release during the first 6 h, which has been attributed to the rehydration of dehydrated phases (Florea et al., 2014; Bogas et al., 2020; Angulo et al., 2015; Wang et al., 2018b). After 6 h CEM I surpassed it and beyond 16 h CEM III/B also exceeded fRCF in cumulative heat release. The small heat release observed for RCF can be related to the presence of some unreacted particles within the material (Oksri-Nelfia et al., 2016; Florea et al., 2014). For pozzolanic reactivity (EN 196-12), fRCF exhibited two distinct peaks: the first peak occurred in the first few minutes and can be associated with the dissolution of the material, whereas the second peak occurred between 15 and 20 h indicating the formation of reaction products (Shah, 2024). This second peak was absent for RCF, demonstrating the enhanced reactivity of fRCF.

Material characterization revealed the physical and chemical changes underlying the improved performance of fRCF. The flash calcination treatment resulted in a reduction in particle size, with the $d(50)$ decreasing from 48.67 μm (RCF) to 36.72 μm (fRCF). This reduction can be associated with chemical and physical changes occurring due to the dehydration process as internal stresses increase and fracture particles due to differences in thermal expansion (Serpell and Lopez, 2015; Real et al., 2020). Simultaneously, the density increased from 2.33 g/cm^3 to 2.68 g/cm^3 because of the loss of physically and chemically bound water (Florea et al., 2014; Kaptan et al., 2024). The TGA and XRD results showed that hydrated phases such as portlandite and ettringite (with densities of approximately 2251 kg/m^3 and 1778 kg/m^3 , respectively) were dehydrated during treatment, while belite and free lime peaks were observed, which have higher densities estimated around 2960–3326 kg/m^3 and 3341 kg/m^3 , respectively (Balonis and Glasser, 2009). The observed mineralogical transformations indicate that flash calcination alters the hydration products and mineral phases present in the RCF. The dehydration of hydration products and formation of phases such as belite (C_2S) and free lime (CaO) may increase the

reactivity of fRCF and thereby contribute to its enhanced binding capacity and strength development (Shui et al., 2008; Serpell and Lopez, 2015; Serpell and Zunino, 2017).

However, fRCF demonstrated different characteristics from primary Portland cement (CEM I). The presence of quartz particles was particularly notable in the XRD results and consistent with the XRF results showing SiO_2 content approximately twice as high in fRCF compared to CEM I, indicating that fRCF contained both cementitious components and siliceous aggregate particles. This fine aggregate contamination likely results from the demolition and crushing stages, indicating potential for process optimization to minimize aggregate content and improve the purity of the recovered cementitious material. Literature reports a wide range of 28-day compressive strengths (4 to 30 MPa) for 100% clinker replacement with thermally treated materials (Carriço et al., 2020). Within this range, thermally treated cement paste samples generally outperform thermally treated RCF, which typically achieves strengths below 10 MPa. This performance difference was attributed to the presence of fine aggregates in RCF reducing the proportion of dehydrated and therefore rehydratable cementitious phases. Additionally, while some of the initial cement phases were identified in fRCF, the phase composition differed from CEM I, with several phases not developed during the upcycling treatment.

The influence of source material characteristics on fRCF performance should also be considered. Temperature and initial water-to-cement (w/c) ratio have been shown to influence strength results, with lower w/c ratios potentially yielding higher strengths due to the presence of more unhydrated particles (Carriço et al., 2020). This suggests that the EoL concrete characteristics may influence the performance of fRCF. In this study, fRCF was obtained from Portland cement based concrete with a w/c ratio of 0.49. Results may change for other cement types, quantities and w/c ratios. Notably, increasing fRCF replacement levels reduced workability, requiring the addition of plasticizer to maintain a constant w/c ratio across mixtures rather than compensating through additional water, which could have significantly impacted strength development. This highlights that workability should be considered in future research when applying fRCF at higher replacement levels. Additionally, higher strengths could be achieved if the fine sand content is reduced or optimized through improved separation techniques.

The potential impact of implementing fRCF as a clinker substitute is substantial. Based on Cembureau data, the EU27 produced 161.1 Mt of cement in 2023, of which approximately 15% was CEM I and 10% CEM III (CEMBUREAU, 2025). Reducing clinker content by 50% in CEM I and 75% in CEM III/B as shown in this research would require approximately 15.7 Mt of fRCF (12.1 Mt and 3.6 Mt, respectively), assuming 30% clinker content in CEM III. The EU generates approximately 858 Mt of construction and demolition waste (CDW) annually, of which 60–70% is concrete, resulting in approximately 558 Mt of available concrete demolition waste (Eurostat, 2024). Based on the Smart Liberator process specifically, it was determined that 1.3% of this concrete waste could be deployed as high-quality clinker replacement material (Rutte Groep, 2022). In this case this equates to 7.3 Mt, potentially covering 46% of the combined clinker reduction target (15.7 Mt). Alternatively, if prioritized exclusively for either cement type, this would be sufficient to cover 60% of the CEM I requirement (12.1 Mt) or could fully satisfy the CEM III/B requirement (3.6 Mt) with 103% excess capacity. The application of fRCF could therefore replace 7.3 Mt of clinker annually in the EU, significantly contributing to the decarbonization of the cement industry.

4.2. Flash calcination process optimization

The flash calcination parameters employed in this study represent initial conditions demonstrating the feasibility of upcycling RCF. While the dehydration temperature of 800 $^{\circ}\text{C}$ (core temperature 700–750 $^{\circ}\text{C}$) with rapid heating and cooling cycles successfully achieved dehydration, significant optimization opportunities exist to enhance treatment

effectiveness and material quality.

Temperature is a critical process parameter. The current regime dehydrated most phases, evidenced by reduced TGA mass loss and the absence of ettringite and portlandite peaks in XRD diffraction patterns. However, optimal phase formations require fine-tuning of the temperature profile. Higher temperatures generally accelerate phase conversions (Teklay et al., 2016), though optimal values may vary by material: Zeraoui et al. (2023) recommended 700 – 1000 °C for sediment, Martirena-Hernández et al. (2023) suggested >850 °C for clays and Safaei (2017) mentioned 650 °C for gibbsite. The optimal temperature for the upcycling of RCF remains undetermined and requires systematic investigation accounting for diverse cement types in EoL concrete. Subsequently, conventional oven-based thermal treatment has not yet identified the temperature range maximizing strength performance. Importantly, optimal temperatures for oven treatment cannot be directly applied to flash calcination due to differences in operating mechanisms. Martirena-Hernández et al. (2023) found that flash calcination required a higher temperature than soak calcination (used at a rotary kiln) for full dehydration. Therefore, determining optimal processing temperatures demands technique-specific experimental programs rather than cross-method extrapolation.

The residence time in the heating zone requires further optimization. Current conditions may provide insufficient time for complete phase transformations. Extending the residence time could enable more complete dehydration and enhance reactive phase formation, though excessive residence times may produce unwanted phases that reduce material reactivity (Teklay et al., 2015, 2016; Overmann et al., 2024). An inverse relationship exists between temperature and residence time: elevated temperatures enhance reaction kinetics and mass transfer coefficients, reducing the time required for target conversions (Teklay et al., 2016). While higher temperatures typically decrease residence time requirements, optimization of this relation remains application specific.

Rapid cooling following thermal treatment presents another optimization opportunity. In clinker production, rapid cooling significantly enhances both material quality and grindability (Peray, 1986). Without it, adverse phase transformations occur: C3A crystallizes while alite redissolves, promoting secondary belite formation (Hewlett, 2004), ultimately degrading the clinker's performance properties. Flash calcination typically employs direct contact with ambient air or controlled heat exchange systems (San Nicolas et al., 2013; Teklay et al., 2015; Lacante et al., 2025). The high surface area to volume ratio of flash calcined particles facilitates rapid heat dissipation. Integrating rapid cooling systems may significantly improve fRCF quality by preventing unwanted phase changes during slow cooling.

The particle size distribution of the feed material also influences flash calcination effectiveness. Finer particles possess higher surface area-to-volume ratios, enhancing heat transfer and promoting uniform heating. Larger particles require longer heat transfer times, extending phase transformations and decomposition rates (An et al., 2025; Teklay et al., 2016). This links particle size to residence time, with finer powders requiring lower residence times to achieve preferred phase transformations (Teklay et al., 2014).

Material throughput represents another critical optimization parameter impacting practical implementation. The current rotating screw conveyor feeding mechanism operates at low speeds, allowing only small material quantities to enter the flash calciner, constraining processing capacity. The screw conveyor system and feeding tube require further development to enhance the throughput capacity, particularly for industrial-scale applications requiring continuous high-volume processing for economic feasibility.

5. Conclusion

This study evaluated the potential of flash calcination as an upcycling treatment for residual cementitious fines derived from Portland-

based concrete using a combined advanced innovative mechanical and thermal recycling process. The findings demonstrated that flash calcination significantly increases the reactivity of the material, thereby enabling higher clinker substitution rates. To what extent this replacement will contribute to a reduction in the overall environmental impact needs to be specifically analysed in future research in order to support a potential claim for environmental footprint improvement. Based on the experimental results, the following key conclusions can be drawn:

- Flash calcination resulted in notable modifications to the physical and mineralogical properties of the fines:
 - o The median particle size decreased (D_{50} reduced from 48.67 μm to 36.72 μm)
 - o The material density increased (from 2.33 g/cm^3 to 2.68 g/cm^3)
 - o Portlandite and ettringite underwent dehydration, accompanied by the formation of new reactive phases.

These transformations confirm that flash calcination thermally activates the material and alters its reactivity properties.

- Flash calcination enhanced the binding capacity of RCF, evidenced by:
 - o A substantially higher cumulative heat release compared with untreated RCF, indicating increased chemical reactivity.
 - o Significantly higher compressive strengths across all clinker replacement ratios and curing ages.

At 100% clinker replacement, fRCF achieved 16.3 MPa compressive strength for both CEM I and CEM III/B based mortars (31.1% and 35.1% of reference strengths for CEM I and CEM III/B, respectively), whereas untreated RCF reached 0 MPa (CEM I) and 11.7 MPa (CEM III/B). These findings demonstrate that flash calcination imparts measurable binding capacity to RCF.

- Mortars containing fRCF in combination with GGBFS achieved compressive strengths comparable to or exceeding reference values up to 75% volumetric clinker replacement:
 - o 101.4% of reference strength at 25% replacement
 - o 99.4% at 50% replacement
 - o 100.7% at 75% replacement

These findings indicate that fRCF provide both binding capacity and an activating effect on GGBFS, enabling high levels of clinker substitution without strength loss.

- Untreated RCF exhibit activating properties towards GGBFS:

Despite showing no measurable compressive strength in CEM I-based mortars at 100% clinker replacement, untreated RCF achieved 11.7 MPa (25.3% of reference strength) in CEM III/B-based mortars. This demonstrates that RCF can chemically activate ground granulated blast furnace slag (GGBFS), even though RCF itself lacks intrinsic binding capacity. Consequently, untreated RCF function not merely as inert filler, but also as chemical activator for pozzolanic or latent-hydraulic materials.

This study demonstrates the potential of flash calcination as an upcycling technique for residual cementitious fines. The process significantly enhances their reactivity, mechanical performance and ability to activate supplementary cementitious materials. The combination of advanced crushing and separation processes to retrieve high-quality RCF with flash calcination enables clinker replacement levels of up to 50% in CEM I and 75% in CEM III/B, corresponding to a total reduction of 7.3 Mt of clinker annually in the EU. However, the current investigation focused exclusively on fines originating from Portland cement-based concrete. End-of-Life concrete streams typically contain multiple cement types and their variability may influence calcination behaviour and performance. Future work should therefore address:

- Influence cement type: Investigate how different binder chemistries affect thermal activation and whether optimization strategies must be tailored to specific cement combinations, including the interaction between fRCF and binder components.
- Influence of fine siliceous aggregates in RCF: Assess whether removing fine aggregates and isolating hydrated cement phases could further improve the performance of flash calcined material.
- Implications for separation and processing strategies: Understanding the role of aggregate contamination will help determine the most effective recycling pathways of maximizing the retrieval of high-quality residual cementitious fines.
- Process scale-up and parameter optimization: Further development of the flash calcination setup is needed to move from the current lab-scale process towards a controllable, industrially scalable treatment, including quantification and optimization of the key process parameters (temperature, residence time, feed rate, throughput, etc.).

CRedit authorship contribution statement

A.T.M. Alberda van Ekenstein: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **R.J. Rutte:** Resources, Investigation. **M. Farchich:** Investigation, Conceptualization. **H.M. Jonkers:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **M. Ottel :** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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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Data availability

Data will be made available on request.

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