cRCP composite cements

The continued development of composite cements has led to the use of a range of supplementary cementitious materials (SCMs). As the availability of SCMs is limited, the cement sector is increasingly interested in sustainable alternatives, including carbonated recycled concrete paste.

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Composite cements contain two or more main constituents. Traditional composite cements contain Portland clinker and supplementary cementitious materials (SCMs) such as fly ash, granulated blastfurnace slag (GBS), and limestone. Over the last three decades, composite cements have gained significant importance in the construction industry due to their numerous benefits. One of the primary advantages of composite cements is their sustainability as the content of the most CO_2-intensive constituent, Portland clinker, is reduced. Composite cements might also offer superior performance characteristics compared to traditional Portland cement. They can have improved durability, increased resistance to chemical attacks, and higher final strength. However, the early compressive strength is lower since the kinetics of the reaction of typical pozzolans and semi-hydraulic materials is slower when compared to Portland clinker. Currently, one barrier for wider application of composite cements is the availability of good-quality SCMs. Most available materials are already used for the production of composite cements or during the production of concrete.

The demand for new SCMs has led to an increased interest in alternative solutions. One such solution is carbonated recycled concrete paste (cRCP), which can be used as a supplementary cementitious material. In addition to being a highly reactive pozzolan, this material also binds CO_2 and enables high added value use of old concrete, resulting in an improvement of the overall environmental impact.

Carbonated recycled concrete paste

cRCP is produced through a two-step process. In the first step, the demolished concrete is recycled and separated, resulting in the production of recycled sand, aggregates, and concrete paste (RCP). While the recycled sand and aggregates can be used for the production of new concrete, the RCP is subjected to a process called enforced carbonation. This carbonation process converts the hydrates from the hydrated cement into calcium carbonate ($CaCO_3$) and alumina-silica gel (Al-Si gel) (see Figure 1). The reaction involves several decalcification reactions, with portlandite being directly transformed into calcium carbonate. In the case of the principal hydrate phase, C-S-H, it initially undergoes decalcification to reach a low Ca/Si ratio, and then decomposes to form the Al-Si gel. Thus, the formation of the Al-Si gel may occur only at high carbonation degrees. This gel has pozzolanic properties, which enable the use of cRCP as an active component in composite cement

It is worth noting that the enforced carbonation process can be conducted at normal temperatures and pressures, which is a significant difference from the carbonation of natural magnesium silicates. This makes upscaling of the enforced carbonation process relatively easy. Under these mild conditions, only the hydrates are carbonated while any remaining aggregates and sand stay unmodified. The properties of the cRCP are modified by the carbonation method and conditions. As a result, the chemical composition of the carbonated paste and the morphology of the carbonation products can be significantly altered. However, the pozzolanic properties of the carbonated paste are independent of these conditions.

Figure 1: scanning electron microscope in the bac scatter electron mode (cross-section across the compacted sample) with elemental map of the carbonated recycled concrete paste showing the main carbonation products

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Hydration mechanisms and performance

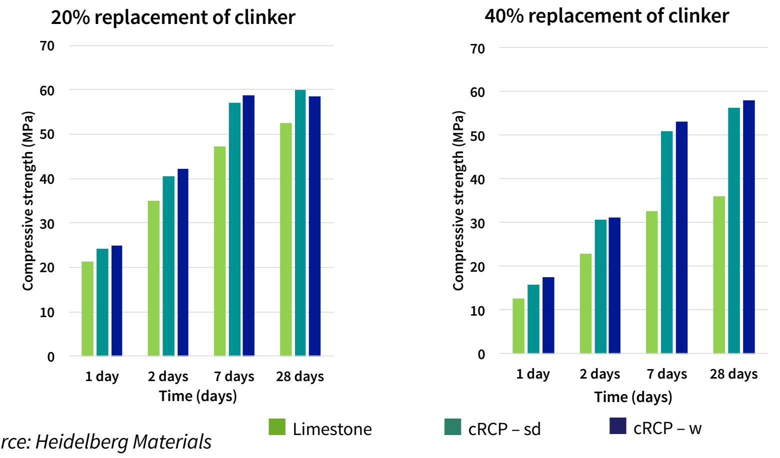
cRCP is an active component of composite cements, contributing to cement hydration and strength formation. It is characterised by its pozzolanic properties: it reacts with portlandite formed during the hydration of Portland clinker to form additional hydrates. The pozzolanic reaction taking place can be summarised as follows:

$$\text{Al-Si-gel} + CaCO_3 + Ca(OH)_2 + H_2O \rightarrow \text{C-S-H} + \text{MC} \quad \text{(Eq 1)}$$

where C-S-H is the C-S-H phase and MC is monocarboaluminate phase.

The mechanism of the reaction of the composite cements with cRCP is similar to those occurring in composite cements containing low-calcium fly ashes or calcined clay and limestone. The main products of the pozzolanic reaction are the C-S-H phase and monocarbonate. The formation of

Figure 2: compressive strength development at 20 and 40 per cent replacement of Portland clinker by different supplementary cementitious materials, cRCP is recycled concrete paste carbonated either in semi-dry conditions (in gas suspension at high relative humidity) or wet conditions (in water suspensions). The carbonation degrees are 80 and 90 per cent, respectively



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these phases results in the reduction of the porosity in the cementitious matrix and its refinement, and consequently increases the mechanical performance of mortars and concretes. Despite these similarities, there is a significant difference between traditional pozzolans and the cRCP. The reaction of the Al-Si gel has a faster kinetic compared to traditional materials. It reacts rapidly to achieve a reaction degree in the range of 70-95 per cent after only seven days from mixing with water. In the case of fly ash glass, the same values are achieved after 90-180 days of reaction, while at seven days the reaction degree is only in the range 0-10 per cent. The high reactivity of the gel is related to its amorphous structure and high surface area being higher than 100m^2/g. The rapid reaction is due to the fact that cRCP has a positive effect on the compressive strength already on the first day. This phenomenon allows for partially overcoming the main disadvantage of composite cements, which is the low early compressive strength (see Figure 2).

The appreciable performance of composite cements with cRCP can be achieved when two prerequisites are met: a high content of hydrated cement in the RCP (ie, low content of aggregates and sand) and a high carbonation degree of cRCP. The former ensures that the content of carbonatable hydrates is high, while the latter is necessary to transform the hydrates into the pozzolanic gel. The sand and aggregates present are inert materials considering the carbonation and hydration reactions. A low carbonation degree results in the presence of hydrated paste in cRCP that is inert from the perspective of the hydration reaction in composite cement.

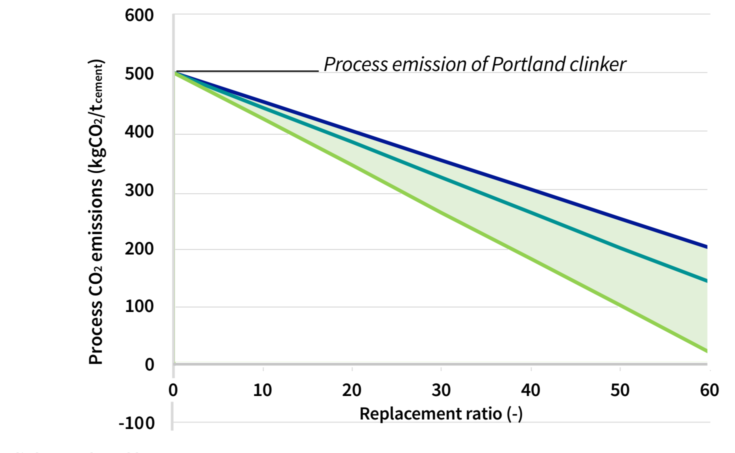
Challenges and opportunities

Although the application of cRCP for composite cement production offers several advantages, it also poses challenges. One obvious challenge is the implementing of new technology, which requires new infrastructure and equipment. Another challenge is related to the high-water demand of cements containing cRCP due to the high surface area of the gel, which must be compensated for by introducing appropriate additives during mortar and concrete production. While the reaction mechanisms and the origin of performance evolution of cements containing cRCP are well recognised, understanding their durability properties has not yet been established. However, the similarities among cements containing cRCP and well-known pozzolanic cements indicate that the new cement will likely exhibit similar durability performance.

Once these challenges are overcome, cRCP has the potential to offer three significant advantages for composite cement production: increased compressive strength, enhanced circular economy and environmental benefits. Composite cements with cRCP exhibit high early compressive strength when compared to the traditional pozzolanic cements, making them more readily implementable in the construction industry. Carbonation of RCP results in the valorisation of this material, allowing for its use as an SCM, and avoiding the stockpiling of the fine fraction from concrete recycling. Therefore, a complete concrete recycling and circular economy are possible. Additionally, the use of cRCP for cement production allows for the sequestration of CO_2 through mineralisation and significant reduction of clinker content in composite cements, offsetting the decreasing availability of traditional SCMs and resulting in a significant reduction in the cement industry's CO_2 footprint.

Once the selective separation and enforced technologies mature, cements almost free of process emissions can be made, as illustrated in Figure 3. The enforced carbonation technology meets several key demands of future cement production – it completes concrete recycling, produces its own SCMs, and thereby (significantly) reduces CO_2 emissions. ■

Figure 3: process emissions, ie, emissions from chemical transformations of raw materials, of composite cements made of Portland clinker replaced by limestone (blue), low-quality cRCP (teal) and high-quality cRCP (light green). For the last case, virtually emissions-free cement can be produced for about 60 per cent clinker replacement ratio. The numbers in the bracket indicate the sequestration potential of RCP



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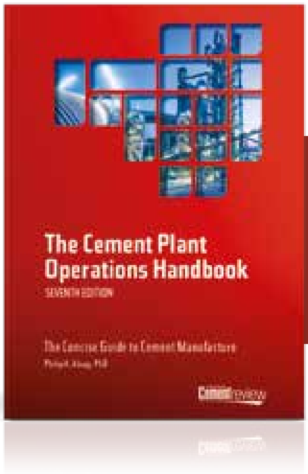

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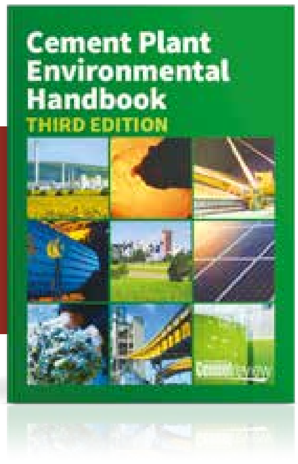

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