

IMPACT OF RECLAIMED WASTEWATER FILTER CAKE MATERIAL ON RHEOLOGY AND COMPRESSIVE STRENGTH OF CONCRETE MADE WITH CEM II AND CEM III BINDERS

Ernests Ozolins¹, Arturs Macanovskis², Nikola Sinica², Maris Tupesis²

¹SIA “Dzelzsbetons MB”, Latvia; ²SIA “Betona petijumu centrs”, Latvia

ernests.ozolins@mbbetons.lv, arturs.macanovskis@bpcentrs.lv,

nikola.sinica@bpcentrs.lv, maris.tupesis@bpcentrs.lv

Abstract. The transition toward “Zero-Waste Factory” principles is a critical requirement for the future concrete industry. These principles shift the focus from merely reducing CO₂ emissions to eliminating waste production by closing the loop on all by-products. One such material is the fine, calcium-rich filter cake (~37% CaO, ~21% SiO₂) generated from the treatment of concrete wastewater. Currently, the filter cake material is generally destined for landfills. This study investigates the feasibility of re-integrating this filter cake material into the production cycle as a filler material, thereby eliminating sludge waste at the factory. The experimental program evaluated the structural and workability impact of this reclaimed material using two distinct binder systems: Portland-limestone cement (CEM II/A-LL) and Blast Furnace cement (CEM III/B) for low-carbon concrete. The chemical composition of dry filter cake was analysed prior to use. The dried dust was introduced as an additive to an existing concrete mix at dosages ranging from 11 to 43 kg·m⁻³, rather than as a cement replacement. The water-to-binder ratio remained constant. Plasticiser dosage was adjusted to ensure the slump flow of concrete was not affected. The binder response varied: the CEM II mix showed a 16% reduction in early strength at 11 kg·m⁻³, though 28-day strength remained unaffected. At higher dosages, the 28-day strength dropped by approximately 10%. Workability remained stable for dosages up to 11 kg·m⁻³, but dropped for higher dosages, resulting in a higher plasticizer dosage. The CEM III mix exhibited a slight strength gain at all ages with dosages up to 43 kg·m⁻³, likely due to the high alkalinity activating the slag fraction. Chloride content of the filter cake material was confirmed at 0.03%, below EN 206 thresholds, ensuring no corrosion risk. These findings confirm that wastewater sludge can be successfully upcycled in concrete production, though further durability testing is required.

Keywords: circular economy, zero-waste manufacturing, sustainable construction, wastewater recycling.

Introduction

The transition toward sustainable, circular economy driven manufacturing in the construction sector represents a massive challenge for the industry. The Portland cement industry is recognized as a primary contributor to greenhouse gas emissions, responsible for approximately six to ten percent of total global carbon dioxide output [1]. In response to stringent environmental regulations and the push toward a zero-waste factory model, the construction materials sector is actively seeking to utilise internal industrial by-products that have historically been destined for landfills. Concrete slurry waste and its dewatered derivative, filtered slurry waste or filter cake, remain as one of the most challenging waste streams generated within ready-mix and precast concrete plants. Characterised by high alkalinity and an abundance of suspended ultra-fines, including unreacted cementitious phases, partially hydrated calcium silicate hydrates (C-S-H), and aggregate dust, filtered slurry waste presents significant disposal and upcycling challenges [2].

Recent studies suggest that reclaimed filtered material can be utilised as a filler or chemical activator within low-carbon binder systems [3]. To successfully integrate this material, it is crucial to understand the underlying physicochemical mechanisms that dictate its behaviour in a cementitious matrix: the Filler Effect and the Dilution Effect. When ultra-fine powders are added to concrete as a partial replacement or addition, two competing mechanisms occur. The dilution effect refers to the reduction in the effective volume of active cement clinker, as the filter cake material is added in addition to already existing mix design, which can negatively impact early strength development [4]. However, in this study, the effects of this mechanism are expected to be limited, whereas the filler effect works to improve the mechanical properties. The small particles serve as heterogeneous nucleation sites, lowering the thermodynamic energy barrier for phase formation and accelerating early-age hydration kinetics [5].

The introduction of high-surface-area additives fundamentally alters the water-film thickness surrounding cement grains. An increase in the particle surface area increases the water demand of the mixture [6]. To maintain a constant water-to-binder ratio, polycarboxylate ether (PCE) superplasticisers are utilised. However, once the surface area of the filler particles exceeds a critical threshold, they become the dominant adsorbents of the PCE molecules [7]. This competitive adsorption leads to a rapid

loss of workability and the entrapment of macroscopic air voids, which directly compromise the density and compressive strength of the hardened concrete [8].

The macroscopic mechanical response of concrete to filtered slurry waste addition varies depending on the underlying chemistry of the binder. Ordinary Portland-limestone cements (CEM II A-LL) rely primarily on direct hydration of clinker phases (C3S and C2S) [9]. In these systems, the filtered slurry waste acts predominantly as an inert physical filler [10].

However, Blast Furnace cements (CEM III/B 32.5N-LH /SR) contain a high proportion of latent hydraulic ground granulated blast-furnace slag (GGBS). The glassy aluminosilicate network of GGBS dissolves exceptionally slowly in neutral water and requires potent alkaline activation to precipitate strength-contributing calcium aluminosilicate hydrate (C-A-S-H) gels [11]. The highly alkaline, calcium-rich nature of the reclaimed filtered slurry waste serves as a chemical activator, triggering the rapid dissolution of the slag and improving the typical delayed early strength gain characteristics associated with CEM III binders [12].

Despite growing interest in concrete wastewater recycling, a critical research gap remains: the majority of published studies either use filter cake as a partial cement replacement or focus on a single binder type, predominantly ordinary Portland cement [3; 15; 16]. The binder-dependent response of the filter cake when used as an additive, rather than a replacement, across contrasting low-carbon binder chemistries (Portland-limestone and blast furnace slag cements) has not been systematically characterised. This distinction is practically significant, since additive use preserves the active clinker volume and therefore tests a different set of physicochemical interactions than replacement-based approaches. Furthermore, existing literature does not address the workability implications of filter cake addition in combination with PCE-based admixtures across a wide dosage range within a single study.

The novelty of the present study lies in three aspects: (1) filter cake is evaluated as a direct additive to the existing mix rather than a cement replacement, isolating its chemical and physical effects at constant clinker content; (2) two chemically distinct low-carbon binder systems, CEM II/A-LL 52.5N and CEM III/B 32.5N-LH/SR, are tested in parallel under identical conditions, enabling direct comparison of binder-dependent responses; and (3) the study spans a wide dosage range (11–43 kg·m⁻³), capturing the threshold behaviour governing both workability and mechanical performance. This study therefore investigates the feasibility of reintegrating dried concrete wastewater filter cake directly into the production cycle as an additive, evaluating its structural, workability, and density impacts across both binder systems with the aim of providing practical guidance for zero-waste concrete manufacturing.

Materials and methods

Materials used in the study:

- CEM II A-LL 52.5 N cement;
- CEM III/B 32.5N-LH /SR cement;
- local coarse aggregate 1 (CA1) – round aggregate with size of 2-8 mm and density of 2.63 t·m⁻³, water absorption of 1.5%;
- local coarse aggregate 2 (CA2) – round aggregate with size of 8-16 mm and density of 2.64 t·m⁻³, water absorption of 1.4%;
- local fine aggregate 1 (FA1) – fine sand with particle size 0-1 mm and density of 2.66 t·m⁻³, water absorption of 0.3%;
- local fine aggregate 2 (FA2) – sand with particle size of 0-4 mm and density of 2.63 t·m⁻³, water absorption of 0.6%;
- PCE superplasticiser;
- tap water;
- dried, filtered, reclaimed concrete fine sludge material with 100% of particles being smaller than 63 µm (no detailed particle distribution analysis has been done) and particle density of 2.55 t·m⁻³.

The dried wastewater sludge material was introduced as an additive to the existing concrete mixes rather than a direct cement replacement. Dosages ranged from 11 to 43 kg·m⁻³. A detailed list of tested parameters and concrete mix proportions can be seen in Table 1. The water-to-binder ratio remained

constant for each series (0.4 for the CEM III series and 0.45 for the CEM II series) to isolate the physical and chemical effects of the filtered slurry waste. PCE dosage was adjusted to maintain similar workability and rheology characteristics. Workability was evaluated using a standard slump cone flow. Compressive strength was tested on 100x100x100 mm standard concrete cubes at ages of 24 hours, 7, and 28 days.

Table 1

Concrete mix proportions used in this study

Reference	CEM II, $\text{kg}\cdot\text{m}^{-3}$	CEM III, $\text{kg}\cdot\text{m}^{-3}$	CA1, $\text{kg}\cdot\text{m}^{-3}$	CA2, $\text{kg}\cdot\text{m}^{-3}$	FA1, $\text{kg}\cdot\text{m}^{-3}$	FA2, $\text{kg}\cdot\text{m}^{-3}$	Water to cement ratio	PCE dosage, % of binder	Filter cake, $\text{kg}\cdot\text{m}^{-3}$
FC – 1	-	360	569	663	95	567	0.40	0.56	0
FC – 2	-	360	569	663	95	567	0.40	0.60	11
FC – 3	-	360	569	663	95	567	0.40	0.78	22
FC – 4	-	360	569	663	95	567	0.40	0.81	33
FC – 5	-	360	569	663	95	567	0.40	1.00	43
FC – 6	360	-	563	657	94	563	0.45	0.60	0
FC – 7	360	-	563	657	94	563	0.45	0.69	11
FC – 8	360	-	563	657	94	563	0.45	0.91	22
FC – 9	360	-	563	657	94	563	0.45	0.97	33
FC – 10	360	-	563	657	94	563	0.45	1.12	43

For precise measurements, scales (LW Measurements HRB series scales) with an accuracy of up to 0.1 g were used to weigh raw materials.

Fifteen litres of concrete were made for each batch of tests. Concrete was mixed in a Collomix Compact Laboratory Mixer POX-S. Fully dried coarse and fine aggregates and cement, together with recycled fine material, the filter cake, were put in the mixer first and mixed for 5 minutes. Then, a mixture of water and the required SP dosage and other additives were poured into the mixer. The concrete was then mixed for further 5 minutes with speed of 60 revolutions per minute. Afterwards, the slump flow test was done in accordance with EN 12350-8 slump flow test standard, with measurements taken 5 minutes after mixing had finished. After demoulding, samples were stored in water tanks at a temperature of 20 degrees Celsius. Each test result consists of two tested samples due to the limitation of the concrete batch size.

Error bars in figures represent the accuracy with which the results were obtained. The error bars in graphs for compressive strength and density comparison represent the overall deviations in the obtained results. Error bars thus show the maximum and minimum obtained values for all of the similar samples tested.

Results and discussion

The XRF data in Table 2 provide a chemical signature of the reclaimed filtered slurry waste material. The material is predominantly composed of Calcium Oxide (36.98%) and Silicon Dioxide (20.59%).

Table 2

XRF data for the filtered material

Chemical compound	Content, %	Chemical compound	Content, %
SiO ₂	20.59	Na ₂ O	0.17
Al ₂ O ₃	4.83	K ₂ O	0.58
Fe ₂ O ₃	2.70	TiO ₂	0.31
CaO	36.98	Mn ₂ O ₃	0.07
MgO	3.42	P ₂ O ₅	0.08
SO ₃	2.25	Cl	0.03

This large concentration of calcium confirms the presence of substantial quantities of portlandite, unreacted calcium silicates (alite and belite), and limestone fines. The silica and alumina fractions are most probably present due to the abrasion and suspension of fine aggregate (quartz sand) particles during the washout process, combined with residual fly ash or slag present in the original concrete batch designs.

This chemical profile classifies the filtered slurry waste material as a highly alkaline, calcium-rich mineral filler. While the material has already undergone partial hydration, rendering it largely without pozzolanic reactivity, its high alkalinity makes it suited for chemical activation of latent hydraulic materials, such as the slag found in CEM III/B binders [13].

A critical metric obtained from the chemical characterization is the water-soluble chloride content, measured at 0.03%. According to the EN 206 standard, the maximum allowable chloride content for reinforced concrete exposed to moisture is restricted to 0.20% by mass of the binder [14]. The filter cake material result confirms the viability of using this material in new concrete production.

The workability and flow retention of fresh concrete were evaluated using standard slump flow tests. For both the CEM II A-LL and CEM III/B systems, workability remained highly stable and within target consistency parameters for filter cake dosages up to $11 \text{ kg}\cdot\text{m}^{-3}$. At this dosage, the fine sludge particles efficiently occupied the interstitial voids between larger clinker grains, potentially improving the packing density without overwhelming the established water film thickness.

However, as the dosage of the filter cake material was systematically increased to $33 \text{ kg}\cdot\text{m}^{-3}$ and $43 \text{ kg}\cdot\text{m}^{-3}$, the required PCE dosage to obtain the required workability was significantly increased as shown in Fig. 1. The cumulative surface area of the added filter cake fines increased the water demand significantly, likely resulting in competitive adsorption of the PCE superplasticizer. Consequently, significant increase in the PCE dosage was required to maintain the necessary flow parameters and prevent severe early stiffening. This behaviour is corroborated by Plank et al. [7], who demonstrated that once the cumulative surface area of fine mineral particles exceeds a saturation threshold, those particles become the dominant adsorbents of PCE molecules, depriving cement grains of the admixture needed for dispersion. More recent work by Liu et al. [17] on wet-ground concrete slurry waste (CSW) confirms that fine CSW particles improve early strength at low substitution rates through pore filling, but at higher surface-area loadings the competitive adsorption effect overtakes any filler benefit, a dynamic directly analogous to the workability losses observed here above $22 \text{ kg}\cdot\text{m}^{-3}$. From an operational standpoint, maintaining dosages between $11 \text{ kg}\cdot\text{m}^{-3}$ and $22 \text{ kg}\cdot\text{m}^{-3}$ prevents excessive chemical intervention by using PCE.

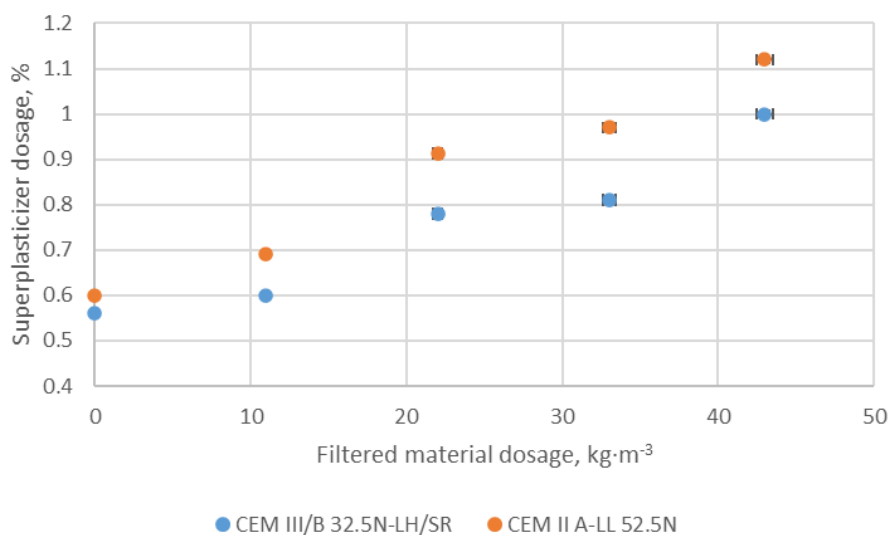


Fig. 1. Required superplasticiser dosage vs filtered material dosage

For the CEM III/B mixtures, the inclusion of the filter cake material had a neutral to positive effect on the concrete density. As shown in Fig. 2 the density remained stable between $2380 \text{ kg}\cdot\text{m}^{-3}$ and

2410 kg·m⁻³ across all dosages, with a slight increase of around 1% when compared to the reference sample. The CEM II A-LL mixtures exhibited a dose-dependent reduction in bulk density. The reference density of approximately 2405 kg·m⁻³ was reduced to approximately 2330 kg·m⁻³ at the dosage of 22 kg·m⁻³ with a reduction of around 3%.

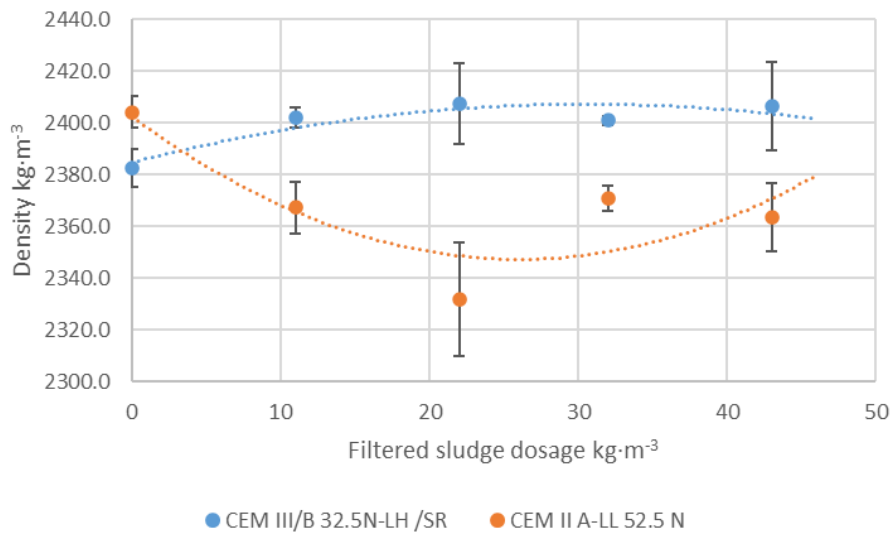


Fig. 2. Density of the samples at 28 days, depending on the filtered sludge dosage

In the CEM II/A-LL 52.5N mixtures, the addition of the dried reclaimed sludge material resulted in a reduction in the compressive strength in almost all cases as shown in Fig. 3. The introduction of 11 kg·m⁻³ of filter cake caused a 16% reduction in the early-age strength at 24 hours and resulted in negligible variance in the 7-day and 28-day compressive strength. While adding more filter cake material improved the early age compressive strength characteristics, it also reduced the later age compressive strength characteristics at 7 and 28 days of age when compared to the reference sample.

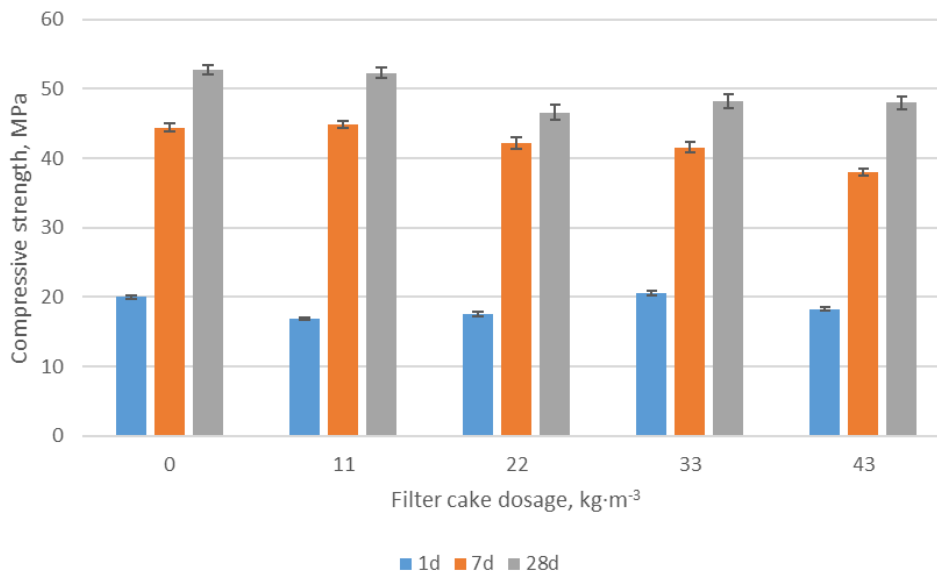


Fig. 3. Compressive strength of CEM II samples

The relative changes in compressive strength at 24 hours, 7 days, and 28 days reflect the different reactions of the two binder chemistries to the addition of reclaimed filter cake material. Because the active clinker volume remained constant across the testing series, early-age strength variations were driven by altered fresh-state workability and chemical activation rather than dilution of the cement matrix. For the CEM II/A-LL 52.5N mixtures, the addition of filter cake negatively impacted strength across all curing stages. The high specific surface area of the added fines increased the mixture viscosity

even with an increase in the PCE dosage, leading to the entrapment of macroscopic air voids during curing, as evidenced by the reduction in sample density. Consequently, an $11 \text{ kg}\cdot\text{m}^{-3}$ addition resulted in a 16% reduction in 24-hour strength, while the highest dosage of $43 \text{ kg}\cdot\text{m}^{-3}$ resulted in 10% reduction in the compressive strength at 28 days. This finding aligns with Govedarica et al. [15], who reported that solidified concrete wastewater treatment sludge, characterised by high $\text{Ca}(\text{OH})_2$ content and negligible pozzolanic reactivity, consistently reduced bulk density and compressive strength in Portland-cement-based mixes, attributing the losses to interference of inert ultra-fine particles with hydration product packing. Importantly, both that study and the present work deal with sludge originating specifically from concrete production washout water, as distinct from municipal or industrial wastewater sludge, which has a fundamentally different chemical and mineralogical composition. Chen et al. [16] similarly found that dry concrete washout waste slurry additions at 10–30% cement replacement reduced the compressive strength in ready-mixed concrete, with losses becoming more pronounced at higher dosages. The present study extends these findings to the additive use case, confirming that even a modest $11 \text{ kg}\cdot\text{m}^{-3}$ filter cake addition is sufficient to produce measurable early-age strength reductions in CEM II/A-LL systems.

The non-linear relationship between filter cake dosage and 28-day compressive strength in the CEM III/B system requires specific mechanistic consideration, particularly given that all dosages produced an increase in 24-hour strength as seen in Fig. 4. This apparent contradiction, early strength gain accompanied by a marginal 28-day reduction at low dosages, is consistent with a threshold-dependent activation mechanism operating in two distinct regimes.

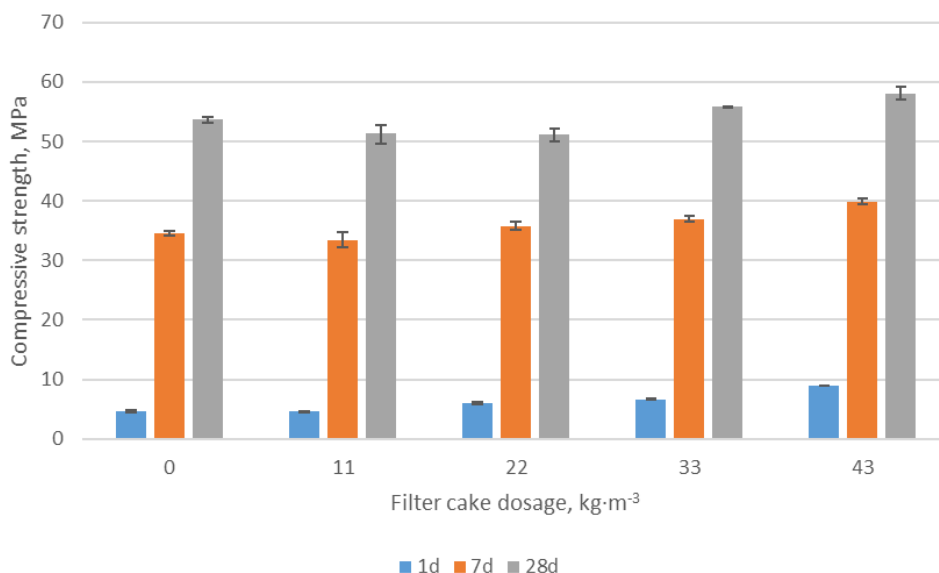


Fig. 4. Compressive strength of CEM III samples

At low dosages ($11\text{--}22 \text{ kg}\cdot\text{m}^{-3}$), the alkaline and calcium-rich filter cake provides a sufficient initial pH spike to accelerate the early dissolution of the GGBS surface layer, explaining the observed gains in 24-hour compressive strength. However, the total alkali content introduced at these dosages appears insufficient to sustain the reaction beyond the early hydration stage. The C-A-S-H gel formed under this moderate alkalinity is likely more diffuse and poorly cross-linked compared to that formed under higher activation conditions, resulting in a marginal reduction in 28-day strength relative to the reference. In effect, the slag likely reacts rapidly but incompletely, consuming the available activator without achieving the dense long-term microstructural development seen at higher dosages.

At dosages of $33\text{--}43 \text{ kg}\cdot\text{m}^{-3}$, the cumulative alkaline load becomes sufficient to both initiate and sustain slag dissolution throughout the curing period. This likely produces the dense, well-developed C-A-S-H gel network responsible for the observed gains at both 24 hours and 28 days. This threshold-dependent behaviour, where early and late strength responses diverge at sub-threshold activator concentrations, is consistent with observations in alkali-activated slag systems reported in the literature [12] and underlines the importance of a minimum effective filter cake dosage when targeting long-term

mechanical performance in CEM III/B concrete. This interpretation is further supported by Liberto et al. [18], who characterised one-part alkali-activated slag systems co-activated with Na_2CO_3 and $\text{Ca}(\text{OH})_2$ and found that $\text{Ca}(\text{OH})_2$ alone provided only moderate early reactivity, adequate cumulative $\text{Ca}(\text{OH})_2$ loading was required to sustain C-A-S-H gel network development beyond the initial hydration peak. Similarly, research on blended CEM III binders has demonstrated that below a critical alkaline activator concentration the protective surface layer on GGBS reforms rapidly, reducing long-term strength gains [18]. These comparisons reinforce the mechanistic conclusion that the non-linear strength response observed here is governed by a $\text{Ca}(\text{OH})_2$ concentration threshold inherent to the CEM III/B slag fraction, rather than being an artefact specific to the present experimental conditions.

Conclusions

1. The mechanical response to the filter cake addition depends on the binder chemistry: it acts predominantly as a physical filler in CEM II A-LL systems and as a chemical activator in CEM III/B systems.
2. For CEM II A-LL mixtures, adding up to $11 \text{ kg}\cdot\text{m}^{-3}$ of filter cake maintains workability and 28-day compressive strength, but reduces 24-hour compressive strength by 16%. Higher dosages reduce 28-day strength by 10%.
3. In CEM III/B mixtures, the alkaline filter cake accelerates early hydration. Dosages up to $43 \text{ kg}\cdot\text{m}^{-3}$ result in a 93% increase in 24-hour strength and an 8% increase in 28-day strength.
4. The high surface area of the ultra-fine filter cake increases water demand. To maintain workability, significantly higher polycarboxylate ether (PCE) dosages are required when filter cake additions exceed $11 \text{ kg}\cdot\text{m}^{-3}$.
5. The filter cake water-soluble chloride content is 0.03%, well below the EN 206 maximum limit, ensuring it can be used without introducing corrosion risks.
6. Re-integrating dried wastewater filter cake into new concrete is a viable step toward zero-waste manufacturing. It is particularly effective in CEM III/B systems, where it offsets delayed early-strength development. However, further durability tests, such as freeze-thaw resistance and carbonation, should be done to further evaluate the effect the filter cake material has on concrete durability.

Author contributions

E. Ozolins: conceptualisation, experimental design, data analysis, writing. A. Macanovskis: experimental work, data collection, review, experimental supervision. N. Sinica: experimental work, data collection, review. M. Tupesis: experimental work, data collection, review.

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