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Evaluating the Mechanical Properties and Carbonation Resistance of High Slag Cement Concretes



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ABSTRACT

Ground granulated blast furnace slag (GGBFS) has been incorporated into cement as a low-carbon alternative to clinker, yet its slower hydration can affect early-age performance. This study evaluates several mechanical properties as well as the carbonation resistance of concretes prepared with high-GGBFS cements, CEM III/A (42 % GGBFS) and CEM III/B (70 % GGBFS), compared against a commonly used reference CEM II/B-M (17 % GGBFS). Several mixes were tested for compressive, direct tensile, flexural tensile, and pull-off bond strengths, as well as elastic modulus, Poisson's ratio, and carbonation resistance for selected mixes. High-GGBFS concretes exhibited moderately lower tensile and pull-off bond strengths at 28 days despite similar compressive strengths, but all mechanical properties equalled or surpassed the reference mix at 91-182 days. Carbonation resistance was slightly reduced in the CEM III/B mixes, and minimal differences were observed in elastic properties. Overall, the findings highlight the potential of high-GGBFS cements to substantially lower the carbon footprint of concrete production without sacrificing long-term mechanical performance, if design and construction practices account for their slower early-age strength development.

Keywords: blast furnace slag, compressive strength, tensile strength, pull-off bond strength, carbonation, modulus of elasticity

1. INTRODUCTION

CEM I, also known as Portland cement, is the primary binder in the manufacture of concrete, one of the most widely used building materials in the world [1]. Production of clinker accounts for 5 % of the global fossil CO₂ emissions [2], since producing 1 ton of CEM I can result in an equivalent CO₂ emissions of 0.7 to 0.8 tons [3, 4, 5]. Around 40 % of those high emissions are

due to the large demand of fuel to reach clinkering temperatures, whereas 60 % is released during the decarbonation of limestone creating clinker that makes up to 95–100 % of CEM I [6]. Many cement producers are developing their cement production to more environmental-friendly direction and lowering the total CO₂ emissions by using alternative fuels like solid recovered fuels (SRF) or biobased fuels (e.g. Finnsementti Oy and Holcim). This has led to the situation where the CO₂ emissions have decreased as the amount of pure fossil-based fuels has lowered.

Some of the common substitutions for clinker are pozzolanic materials, such as fly ash and silica fume, which react with portlandite and water forming hydration products with binding properties [7]. Another widely used substitution for clinker is ground granulated blast furnace slag (GGBFS), which is the focus of this study. GGBFS is a by-product of iron (pig iron) production, which contains similar oxides as clinker, but in different ratios. GGBFS displays latent hydraulic properties, such that in the presence of water and a suitable activator, it produces hydration products that contribute to the strength of concrete [7]. The activity of GGBFS largely depends on its glass content, chemical composition and fineness of the powder [8].

Generally, GGBFS shows a slower rate of hydration, in comparison to CEM I [9, 8]. In addition, the hydration of GGBFS only starts in the presence of clinker, sulphates, or calcium hydroxide, to form calcium-silicate-hydrate (C-S-H), the main hydration product providing strength to concrete [9]. Due to the slower reaction rate, especially during the first 28 days, a common replacement range of CEM I with GGBFS in concrete mixes varies from 30 % to 50 %, whereas higher rates such as 85 % are mainly used in massive structures to avoid higher heat of hydration [10].

According to the standard EN 197-1 [11], cement is classified as CEM I, when it comprises at least 95 % of clinker, while CEM II/B-S, a slag-blended cement, can contain as much as 35 % GGBFS. Other slag-blended cements, such as CEM III/A and CEM III/B, can contain up to 65 % and 80 % of GGBFS respectively. The equivalent CO₂ emissions for producing 1 ton of GGBFS can vary from 60 [12] to 90 [13] kg. According to the environmental product declaration (EPD) published by Finnsementti Oy, the Finnish GGBFS distributor, the emissions of one ton of GGBFS is 69 kg [14] . . This is only 10% of the emissions of CEM I. Such large difference in emissions significantly reduces the carbon footprint of GGBFS-blended cements. In addition, the inclusion of GGBFS in concrete improves its resistance to sulphate attacks and chloride-induced corrosion, by decreasing its overall porosity [15] due to the consumption of calcium hydroxide as GGBFS hydrates [16].

There is not yet a harmonised practice in Europe for allocating emissions from iron production between pig iron and blast furnace slag. Three different allocation models are being considered: a fixed agreed value, physical allocation, or economic allocation based on product prices. Regardless of which calculation method is used, the total physical CO₂ emissions remain constant only the allocation between cement and pig iron changes. This is important to remember.

Currently, price-based allocation is recommended, whereby 1–1.4% of iron production emissions are allocated to blast furnace slag. In addition, the emissions from processing the slag into a suitable cement substitute must be included. In Finland, the availability of blast furnace slag currently appears favourable, with supply from Finnish sources expected to continue well into the 2030s. This is because SSAB Finland does not anticipate investing in hydrogen-DRI-EAF technology for steel production until the 2030s [17].

In light of the urgent need to reduce carbon emissions and mitigate the effects of climate change, researchers have investigated different properties of concretes manufactured with slag-blended cements [18-24]. Tsakiridis et al. [21] examined the compressive strength of mortars made with CEM I and those with a 10.5 % replacement of GGBFS, finding no significant differences in their compressive strengths. Qiang et al. [22] investigated both the compressive strength and carbonation resistance of mixes containing 15 % and 30 % GGBFS. At 15 % replacement, there was a slight reduction in early compressive strength but no significant effect on carbonation resistance. However, at 30 % GGBFS, early compressive strength lowered considerably, and carbonation resistance was notably weakened.

Tahwia et al. [18] investigated the compressive, tensile, and flexural strengths, as well as the elastic modulus of high-slag ultra-high-performance concretes. The percentage of CEM I replaced by slag varied from 0 to 75%, and all mixes included an addition of 15% silica fume by binder weight. A decrease in the early compressive strength (1-, 7-, and 28-day) was observed as was the case in other research, however, in this research even the late compressive strengths (90- and 180-day) were lower than that of the reference, which continued to decrease as the amount of slag was increased. A similar decrease was observed in the splitting tensile and flexural strengths, as well as the elastic modulus measured at 28 days. However, these findings may reflect the combined effect of slag and silica fume rather than slag replacement alone.

Teng et al. [19] assessed the compressive and flexural strengths, as well as the elastic modulus of concrete containing 30 % ultra-fine GGBFS. Compared to the reference concrete with no GGBFS, a significant improvement was observed in all tested properties of concretes with ultra-fine GGBFS, which is expected due to the higher hydration rate compared to that of regular GGBFS. This improvement was more pronounced in mixes with lower w/c ratio, demonstrating greater strength gains at both early and late ages. Nonetheless, grinding GGBFS into its ultra-fine state is very costly and its additional milling requires extra energy, which increases its carbon footprint.

Carbonation of high-slag cements was researched by Rivera et al. [25], where accelerated carbonation of cement paste specimens containing 50% GGBFs and 50% CEM I were compared to those made with 100% CEM I. Specimens with 50% GGBFs captured around 20% more CO₂ compared to the reference. Furthermore Helsing and Utgenannt [26], investigated the impact of carbonation of concretes with high GGBFS content (up to 65 %) on their salt frost resistance and compressive strengths. They found a clear increase in surface scaling for higher GGBFS contents, which was further increased by factors of 3-5 after exposure to 1% CO₂.

Similar surges in scaling were observed by Iqbal et al. [24], who increased the GGBFS content up to 80%. In addition, they measured the compressive strength at 7, 28, and 91 days. A decrease was observed in the 7- and 28-day compressive strengths for concretes containing 70% and 80% GGBFs compared to CEM I-concretes. However, in comparison to the reference concrete, the 91-day compressive strength of samples with 70% GGBFs was 10% higher, and those with 80% GGBFs were 35% lower. Nevertheless, this study did not investigate other mechanical properties such as direct or flexural tensile strengths.

Given the lack of extensive research investigating the mechanical properties of concretes produced with commercially available high-slag cements, this study aims to provide practical insight for the construction industry into the properties of concretes made with 100 % CEM III/A and CEM III/B as they are supplied by manufacturers. Concretes manufactured with these low-carbon alternatives are compared with the most used cement in Finland, CEM II/B-M (brand name Oiva).

The investigation covers the mechanical properties most specified in construction projects: compressive, direct tensile, flexural tensile, and pull-off bond strengths, as well as the elastic modulus, and Poisson's ratio. In terms of durability, the research evaluates carbonation resistance of the tested concretes. Elastic properties and carbonation resistance were evaluated only for CEM III/B and CEM II/B-M. By addressing these aspects, this study seeks to provide a more comprehensive understanding of the performance of high-GGBFS concretes without relying on either chemical or thermal activation, hence facilitating a smoother transition towards more sustainable concrete production.

2. EXPERIMENTAL METHODS

2.1 Constituents and mix proportions

In this research, three different cements were used. CEM II/B-M (S-LL) 42.5N, the most used cement in Finland, was used as the reference cement, to which the other two were compared. The other cements used were CEM III/A 52.5L and CEM III/B 42.5L – LH/SR. The compositions of the cements, their fineness and their global warming potential (GWP) are presented in Table 1.

Table 1 – Binder types, their composition, fineness and global warming potential (GWP)

Binder type	GGBFS [%]	Limestone [%]	Clinker [%]	Fineness, Blane [m ² /kg]	GWP* [kg- CO ₂ eq./ton]
CEM II/B-M (S-LL) 42,5 N	17	8	75	510	567
CEM III/A 52,5 L	42	4	54	420	446
CEM III/B 42,5 L LH/SR	70	2	28	530	251

*Finnsementti Oy's declared GWP values

As previously mentioned, both CEM III/A and III/B have higher replacement ratios of GGBFS than CEM II/B, which translates to a lower GWP. Specifically, CEM III/A reduces CO₂ emissions by approximately 23 % per ton compared to CEM II/B, while CEM III/B achieves a reduction of over 50 %. The chemical compositions of each of the three binders are presented in Table 2. It should be noted that the values represent the major oxide constituents only. Loss on ignition (LOI) and alkali oxides such as K₂O and Na₂O are not included, as these were not reported in the available data.

Table 2 – Chemical composition of the binders according to XRF analysis

Binder type	Ca [%]	Si [%]	Al [%]	Fe [%]	Mg [%]	S [%]
CEM II/B-M (S-LL) 42,5 N	58	21	6	3	3	3
CEM III/A 52,5 L	52	25	8	2	6	4
CEM III/B 42,5 L LH/SR	44	29	11	1	8	3

Aggregates used in this study were granitic aggregates and consisted of 0–5 mm crushed rock fines, 0–8 mm natural sand, and 8–16 mm crushed aggregate, and had water absorptions of 0.3 %, 0.4 %, and 0.3 %, respectively. These correspond to nominal aggregate sizes of 5 mm, 8 mm,

and 16 mm. The moisture content of each aggregate fraction was measured before casting, and the necessary water and aggregate amount corrections were made.

A total of eight mixes were manufactured for this research as shown in Table 3. This study contains two main test groups: the flexural and tensile strength (FTS) group, and the elastic properties and carbonation (ELC) group. The Mix IDs in Table 3 identify the test group, with the number after the hyphen indicating the GGBFS percentage. For instance, FTS-17 is the mix tested for flexural and tensile strength and made with CEM II/B-M (S-LL) 42,5 N, which contains 17 % GGBFS.

Workability was adjusted using MasterGlenium SKY 660 (Master Builders Solutions, Finland), with dosages listed in Table 3. All mixes had a water-to-cement ratio of 0.6, except for ELC-70, which required a reduced water content (water-to-cement ratio = 0.58) due to its higher slump despite receiving less than half the superplasticizer dose of its counterpart, as will be shown in the results section. The target compressive strength class of all mixes was C30/37, equating to a minimum cubic compressive strength of 37 MPa at the age of 28 days. In turn, the target flexural tensile strength and direct strength are 8 % (3 MPa) and 16 % (6 MPa) of the compressive strength, respectively.

Table 3 – Mix designs for the three test groups: FTS (Flexural and Tensile Strength), BON (pull-off Bond strength), and ELC (Elastic properties and Carbonation). Saturated surface dry masses are presented for aggregates.

Test group	FTS			BON			ELC	
Mix ID	FTS-17	FTS-42	FTS-70	BON-17	BON-42	BON-70	ELC-17	ELC-70
Cement (kg/m ³)	320	320	320	330	330	330	320	320
Sand 0/8 (kg/m ³)	1323	1355	1357	1301	1352	1349	933	938
Crushed aggregate 8/16 (kg/m ³)	542	546	541	543	554	553	765	769
Crushed aggregate 0/5 (kg/m ³)	0	0	0	0	0	0	182	182
Superplasticizer (kg/m ³)	1.92	1.28	0.96	1.55	2.2	2.2	1.92	0.96
Water-to-cement ratio	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.58

2.2 Methods

Testing overview

For each mix, the slump, air content, and the fresh density were measured according to the standards SFS-EN 12350-2 [27] and SFS-EN 12350-7 [28]. In addition to the other tested properties, the compressive strength was measured according to the standard SFS-EN 12390-3 [29]. Compressive strength tests were performed on two 100-mm cube specimens for the FTS group, whereas for group ELC three 150x300 mm cylinders were tested under compression.

Specifically, the FTS group was evaluated at 28 and 91 days, while the ELC group was tested only at 91 days. Note that CEM III/A was not included in the ELC group due to project-specific constraints prioritizing III/B and II/B-M in elastic and carbonation testing. The casting, sampling, and testing procedures for each tested property are as outlined in the following subchapters.

Direct tensile strength testing

Two slabs were cast for direct tensile strength tests, each measuring 760x570x200 mm³. Until reaching testing ages, the slabs were cured and stored under a plastic sheet at a temperature of 20±2 °C. Six cores were drilled, each with a diameter of 73 mm and heights ranging from 73 to 120 mm. The tensile strength was determined at ages 28 and 91 days, as per the standard SFS 5445 [30]. After securing the cores into the tensile testing machine, a uniaxial tensile load was applied until failure of the sample, and the maximum force was recorded to calculate the tensile strength according to Equation 1:

$$f = F/A \quad (1)$$

where f is the tensile strength (MPa), F is the load at failure during tension (N), and A is the cross-sectional area of the specimen (mm²).

Four-point bending test

Three beams measuring 500x100x100 mm³ were cast to evaluate the flexural tensile strength of each FTS mix. Following SFS-EN 12390-5, each beam was positioned on two support rollers and subjected to a four-point bending test. The maximum load recorded at failure was then used in Equation (2) to calculate the flexural tensile strength:

$$f_{ct,fl} = \frac{F \times l}{d_1 \times d_2^2} \quad (2)$$

where $f_{ct,fl}$ is the flexural tensile strength (MPa), F is the maximum load (N), l is the distance between the lower rollers (mm), and d_1 and d_2 are the lateral dimensions of the specimen (mm); d_1 representing the breadth and d_2 representing the height of the cross section.

Pull-off bond strength testing

Two slabs per BON mix, measuring 760x570x200 mm³, were cast for assessing the pull-off bond strength according to SFS-EN 1542 [31]. Both slabs were cured for seven days under plastic sheeting at a temperature of 20±2 °C. After seven days of curing, one slab was kept continuously covered between tests, while the other had its sheeting permanently removed.

Five measurements were taken from each slab, by gluing steel pull-heads onto the test areas using epoxy resins and left to harden for 24 hours. Followingly, an 80-mm drill head was used to drill around 5 mm into the concrete to limit the pull-off to the desired test area, as shown in Figure 1. Testing was carried out using the pull-off machine, F20D Easy M2000, which measures the tensile bond strength based on Equation 3:

$$f_h = \frac{4F_h}{\pi D^2} \quad (3)$$

where f_h is the bond of the test specimen (MPa), F_h is the failure load (N), and D is the mean diameter of the test specimen (mm).

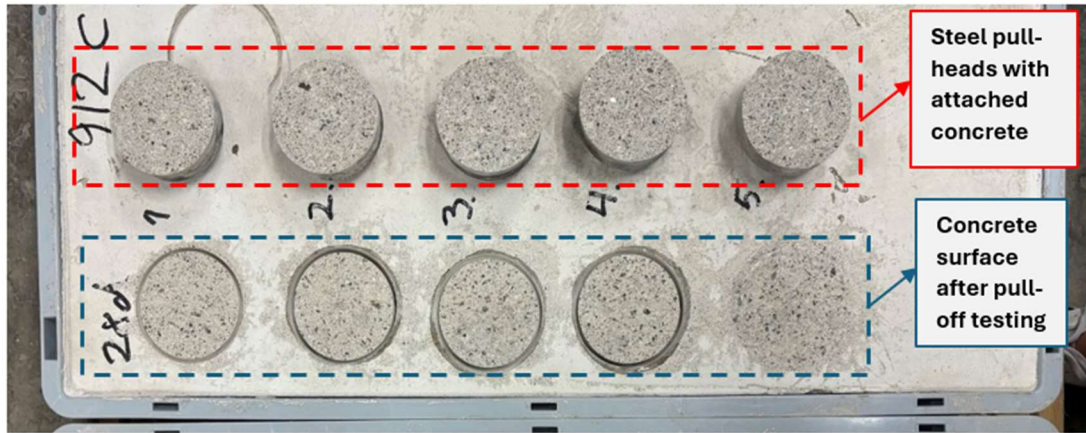


Figure 1 – Post pull-off testing from specimen BON-42 at the age of 28 days, in accordance with SFS-EN 1542. Note: the top row shows the steel pull-heads with attached concrete cores, while the bottom row shows the exposed concrete surface after testing.

Elastic properties testing

Method A in the standard SFS-EN 12390-13 [32] was used to determine the elastic modulus of concrete at the age of 91 days, as shown in Figure 2. Samples were cured under water and take out of water on previous day before testing. Last 24 h before testing samples were stored in laboratory environment at $20 \pm 2^\circ\text{C}$. Three cylinders measuring 150x300 mm were cast per each mix, and their elastic modulus was calculated according to Equation 4:

$$E_{c,s} = \frac{\Delta\sigma}{\Delta\varepsilon_0} = \frac{\sigma_a^m - \sigma_b^m}{\varepsilon_{a,1} - \varepsilon_{b,0}} \quad (4)$$

where $E_{c,s}$ is the elastic modulus (MPa), $\Delta\sigma$ is the difference between the measured upper stress (σ_a^m) and lower stress (σ_b^m) (MPa), and $\Delta\varepsilon_0$ is the difference between the average strains at the upper ($\varepsilon_{a,1}$) and lower stress levels ($\varepsilon_{b,0}$). The suitable upper and lower stresses were determined by testing three 150x300 mm cylinders from each mix under compression according to SFS-EN 12390-3 [29].



Figure 2 – Test setup of a 150 × 300 mm concrete cylinder for measuring elastic modulus and Poisson's ratio under compression from the ELC (elastic properties and carbonation) group

In addition to the elastic modulus, Poisson's ratio was measured from the same cylinders using two 60-mm long strain gauges, positioned perpendicular to each other. One gauge measured the longitudinal strain, whereas the other measured the transverse strain, and Poisson's ratio was determined from Equation 5:

$$\nu_{c,s} = -\varepsilon_t / \varepsilon_l \quad (5)$$

where $\nu_{c,s}$ is Poisson's ratio, ε_t is the transverse strain, and ε_l is the longitudinal strain.

Carbonation resistance testing

Two 100x100x500 mm³ prisms measuring were cast to evaluate resistance to carbonation as per SFS-EN 13295 [33]. After casting, the samples were covered in film for 24 hours, then they were demoulded and rewrapped in film for 48 hours. Samples were then unwrapped and cured for 25 days in a standard laboratory climate of (60 ± 10) % RH at 20 ± 2°C. After curing, the samples were exposed to an accelerated carbonation environment containing 1 % CO₂ at a temperature of 21 ± 2°C and relative humidity of 60 ± 10 %.

Carbonation depth measurements were taken monthly by splitting the prisms and immediately spraying the freshly exposed surfaces with a 1 % phenolphthalein solution in ethanol. The non-carbonated areas turned dark pink (pH > 9), while carbonated regions remained colourless. Measurements were recorded at five points along each exposed face, and the average carbonation depth was calculated over a period of three months. As shown by Roy et al. [34], the carbonation rate, K_s (mm/year^{0.5}), can be calculated from Equation 6:

$$K_s = d/t^{0.5} \quad (6)$$

where, d is the carbonation depth (mm), and t is the time (years).

3. RESULTS AND ANALYSIS

3.1 Fresh concrete properties

Table 4 presents the slump, air content, and fresh densities of the tested concrete mixes. All mixes fell within slump class S4, with values ranging from 160 to 200 mm. The exception was the FTS-42 mix, which showed a slump of only 60 mm, classifying it as a concrete with the slump class of S2. Due to its significantly lower workability, this mix required prolonged compaction to ensure proper entrapped air expulsion. The measured air content averaged 2.1 % ranging from 1.2 % to 2.8 %, while the densities averaged 2388 kg/m³ ranging from 2349 kg/m³ to 2410 kg/m³. Both sets of values are within their expected ranges.

Table 4 – Slump, air content and fresh densities of the tested mixes. Note: the fresh density measurement for FTS-42 was missing.

Mix ID	Slump (mm)	Air content (%)	Fresh density (kg/m ³)
FTS-17	175	2.0	2410
FTS-42	60	1.2	–
FTS-70	180	1.9	2398
BON-17	170	2.6	2385
BON-42	180	2.8	2349
BON-70	200	2.6	2363
ELC-17	160	1.8	2404
ELC-70	180	1.5	2408

3.2 Compressive strength

The measured compressive strengths and their calculated mean values are presented in Figure 3: part (a) for the FTS group, and (b) for the ELC group. The FTS group shows an average cube strength (100 mm) range of 0.8 MPa, with the highest difference of 1.5 MPa found in the 28-day FTS-70 specimens. In contrast, the ELC-70 mix exhibits a 3.3 MPa 2:1 cylinder strength difference among the three 91-day cylinders. These variations are within expected limits for small specimen sets and does not affect the broader conclusions drawn from the data.

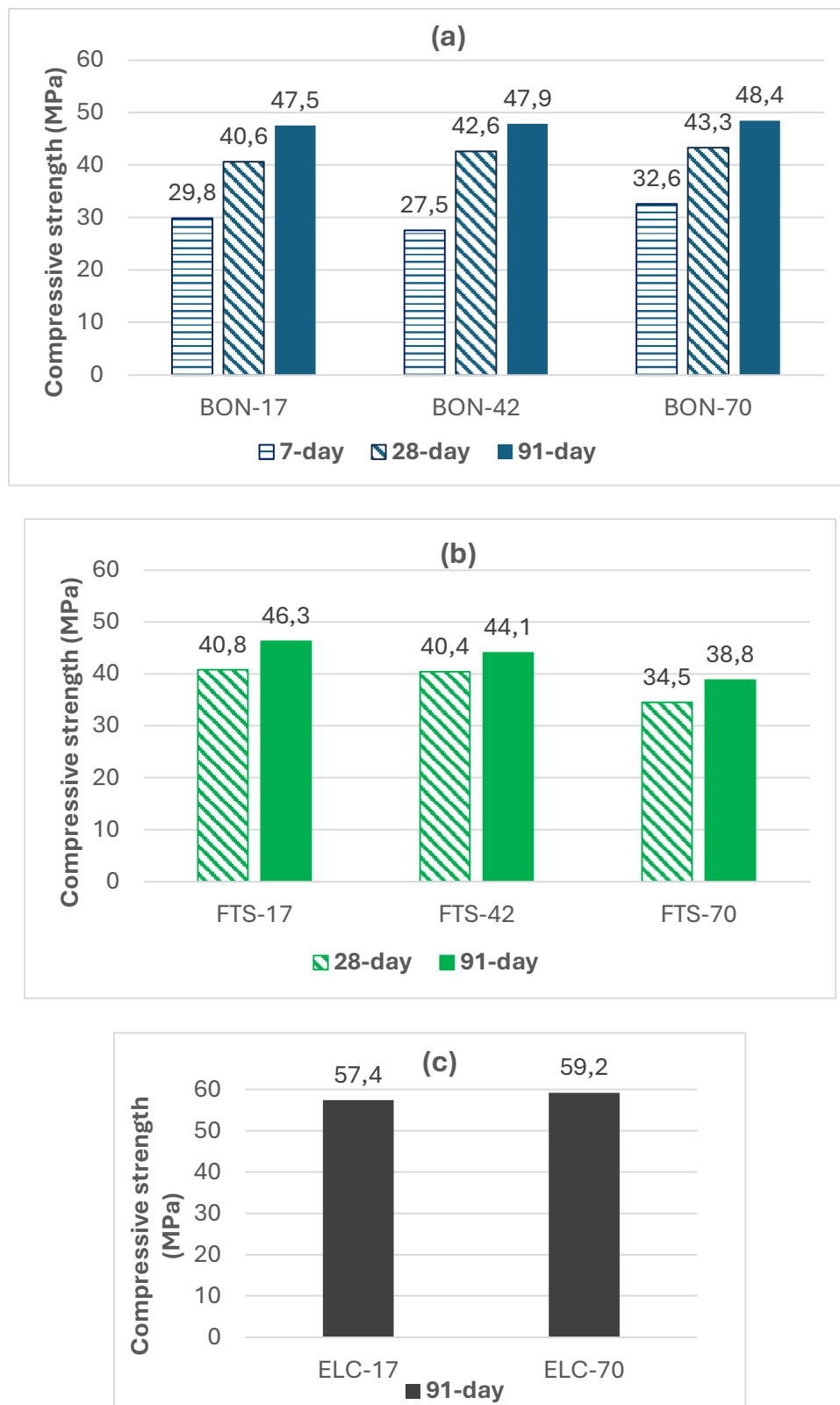


Figure 3 – Compressive strengths of 100-mm cubes cast from (a) BON mixes (pull-off bond strength), (b) FTS mixes (flexural-tensile strengths), and (c) ELC (elastic properties and carbonation) mixes.

Figure 3a presents the compressive strength development of the BON group at 7, 28, 91, and 182 days. At 7 days, increasing the GGBFS replacement rate from 17% (BON-17) to 42% (BON-42) resulted in only a minor strength reduction of 1.4 MPa, while a 70% replacement (BON-70) yielded a 3.7 MPa strength increase. This, however, changed at 28 days, where both BON-42 and BON-70 demonstrated higher compressive strengths than BON-17 by 2.3 MPa and 2.9 MPa, respectively. It should be noted that, all mixes exceeded the recipe's target compressive strength of 37 MPa, already at 28 days.

The 91-day results showed a similar behaviour, with both higher-GGBFS mixes maintaining slightly greater strengths than BON-17. By 182 days, BON-42 achieved the highest strength at 51.4 MPa, followed by BON-70 (49.7 MPa) and BON-17 (48.5 MPa). These results demonstrate that substantial clinker replacement with GGBFS (up to 70%) might enhance compressive strength as early as 7 days, with this beneficial effect persisting or even increasing over time, particularly for the 42% GGBFS replacement level in CEM III/A. It should also be noted that the strength class for CEM III/A was the highest of 52.5 MPa compared to 42.5 MPa for the other two, which agrees with the previous results.

Figure 3b shows the cube strengths (100 mm) of the FTS group at 28 and 91 days. At the age of 28 days, both FTS-17 and FTS-42 show similar strengths of 40.8 and 40.4 MPa, whereas FTS-70 showed around a 15 % reduction. This lowering left FTS-70 lacking by 2.5 MPa from the recipe's target compressive strength. By 91 days, the reduction trend continued, where the compressive strength of FTS-70 remained about 7 MPa lower than that of FTS-17. Moreover, the strength of FTS-42 did also decrease but only by 2 MPa in comparison to FTS-17's. However, by the age of 91 days, all tested FTS cubes exceeded the target compressive strength of 37 MPa.

Such a decrease in compressive strength at later ages is not common for GGBFS-blended cement. However, some researchers [35] have reported similar trends, where they observed a 10-percentage-point decrease in the 90-day compressive strength of concrete when GGBFS replacement exceeded 50 %. This reduction increased to 20 percentage points as the water-to-binder ratio rose from 0.5 to 0.7. In addition, a 35% decrease at 91-day compressive strength was observed by Iqbal et al. [24] at GGBFS content of 80%.

These findings highlight that compressive strength reductions at later ages can occur in GGBFS-blended concretes. In this study, a lower later-age compressive strength was observed only in the FTS series, whereas the BON and ELC series did not show the same trend. For this reason, no firm conclusion can be drawn from the FTS compressive strength results alone. However, it should be noted that the FTS group was primarily intended for flexural and direct tensile strength testing, and the compressive strength results serve as supplementary data.

As for the ELC group shown in Figure 3c, ELC-70 showed a slightly higher compressive 2:1 cylinder strength than that of ELC-17 at 91 days. While the difference was only around 1.8 MPa, both ELC-17 and ELC-70 showed compressive strengths much higher than the target compressive strength of the recipe.

3.3 Flexural tensile and direct tensile strengths

The flexural tensile, acquired from the four-point test, and the direct tensile strength developments at 28 and 91 days are shown in Figures 4a and 4b. For flexural strength at 28 days, all mixes behaved similarly and surpassed the target strength of 6 MPa. Specifically, FTS-70 and FTS-42

both reached 6.6 MPa, just 0.5 MPa below FTS-17 (7.1 MPa). By 91 days, however, FTS-70 achieved the highest flexural strength (7.1 MPa), surpassing FTS-42 (6.7 MPa) and FTS-17 (6.6 MPa). *Thus, the flexural strengths were of similar magnitude at both ages, with FTS-70 showing the highest value at 91 days.*

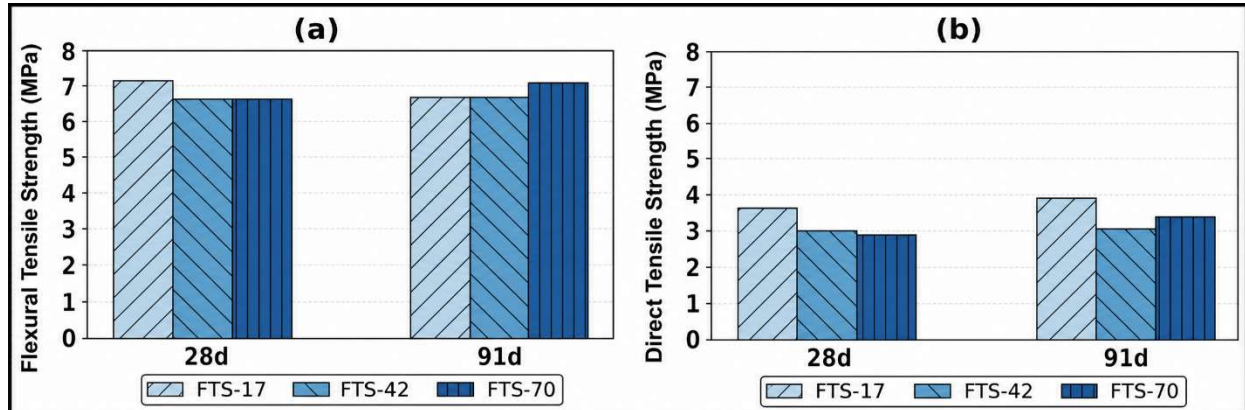


Figure 4 – (a) Flexural tensile and (b) direct tensile strengths of the FTS (flexural-tensile) group, both tested at the ages of 28 days and 91 days.

Direct tensile strength results revealed different trends. At 28 days, FTS-17 led with 3.6 MPa, while FTS-42 and FTS-70 were ~18 % lower (3.0–2.9 MPa), both barely reaching the target direct tensile strength. By 91 days, FTS-70 showed the most significant improvement (+17 %, to 3.4 MPa), though it remained 13 % below FTS-17 (3.9 MPa). FTS-42 exhibited the lowest tensile strength at 91 days (3.1 MPa). Overall, the direct tensile strengths varied between the mixes, but all values remained within a relatively narrow range. .

3.4 Pull-off bond strength

Figure 5 shows the pull-off bond strengths for both the covered and uncovered specimens from the BON group. All BON specimens show increasing of bond strength with age; from 28 to 182 days due to the development of strength and hydration over time. As for the impact of covering during storage, covered BON-17 displayed lower 28-day bond strength than the uncovered specimen. However, by 91 days, it approached the uncovered result and ended up slightly higher at 182 days..

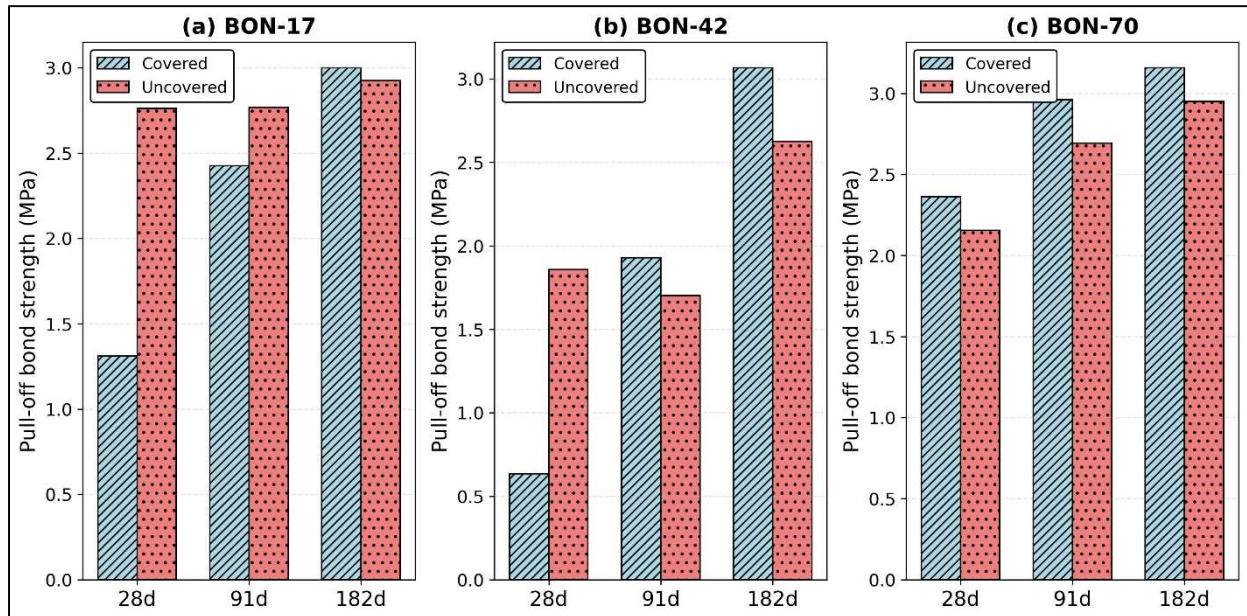


Figure 5 – Pull-off bond strengths of the BON group. Note: Specimens were cured under plastic sheets for seven days, after which the covers were removed from the uncovered specimens, while the covered ones remained under plastic sheets for the 182 days.

A similar trend, but even more pronounced is observed in BON-42, as the bond strength of the covered specimen at the age of 28 days is less than third that of the uncovered specimen. However, at 91 and 182 days, the covered specimen showed slightly higher bond strengths. At the highest GGBFS replacement rate of 70 %, the covered BON-70 specimens displayed consistently slightly higher bond strengths at the three testing ages.

As for the difference in bond strength across the three mixes, the 28-day bond strength of BON-42 remains the lowest, being below 2 MPa, whereas both BON-17 and BON-70 exceed 2 MPa. This trend persists, at the age of 91 days, when both BON-17 and BON-70 exceed the 2.5 MPa threshold, while BON-42 barely reaches close to 2 MPa. This however changes at the age of 182 days, as all three specimens average about 3 MPa of bond strength, with BON-70 being slightly higher.

3.5 Elastic modulus and Poisson's ratio

The measured values of the elastic moduli and Poisson's ratios for the ELC group are presented in Table 6. Overall, the values remain quite similar across the mixes, with only a small increase in the elastic modulus and Poisson's ratio as the GGBFS replacement ratio increases. Specifically, the elastic modulus for ELC-70 is 4 % higher than that of ELC-17, suggesting a slightly stiffer concrete at a higher replacement rate of slag. Similarly, Poisson's ratio showed a modest increase by 5 % for ELC-70 in comparison to ELC-17. This indicates a slightly more lateral deformation at the higher GGBFS replacement ratio. These minor changes suggest that the increase of GGBFS replacement rate does not have a significant impact on the elastic properties of concrete.

Table 6 – Measured Elastic modulus ($E_{c,s}$) and Poisson's ratio ($\nu_{c,s}$) for the ELC (Elastic properties and Carbonation) group

Mix ID	Elastic modulus (GPa)	Poisson's ratio
ELC-17	35.6	0.213
ELC-70	37.0	0.224

3.6 Carbonation depth

Figure 6 shows the measured carbonation depth for ELC-17 and ELC-70 over the period of three months due to accelerated carbonation. As presented in Figure 6, ELC-17 consistently exhibits a carbonation depth about 3 mm smaller in comparison to ELC-70's, across the three months of testing. The final carbonation depth was around 1.5 times greater for ELC-70 compared to ELC-17. Since a lower water-to-cement ratio would generally be expected to reduce carbonation depth, this difference is unlikely to explain the greater carbonation measured for ELC-70.

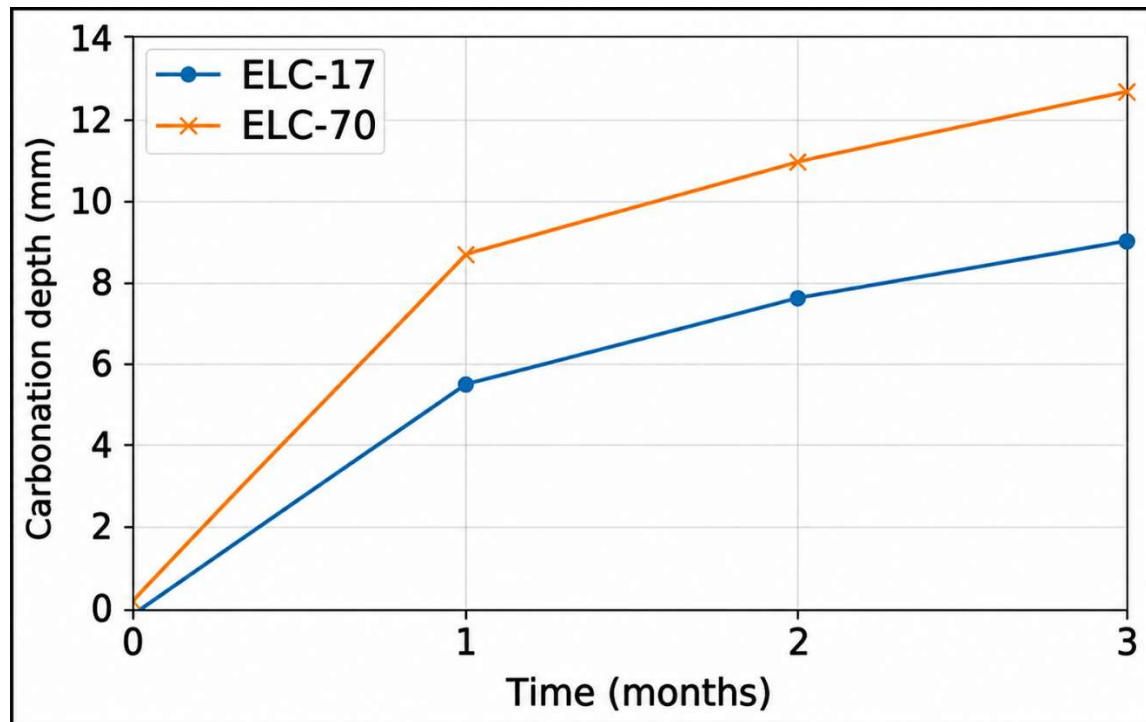


Figure 6 – Measured carbonation depth over time due to accelerated carbonation (CO_2 concentration = 1 %, temperature = 21 ± 2 °C, and RH = 60 ± 10 %) for the ELC (Elastic properties and Carbonation) group.

Higher GGBFS content leading to higher carbonation depths was demonstrated by Iqbal et al. [24]. Specifically, they [24] found that at 80 % GGBFS content, the carbonation depth was two times greater than that of CEM I concrete. This trend is consistent with results of this research, where the lower ratio (1.5x vs 2x) can be attributed to the lower concentration of CO_2 in our research (1% vs 3%). In addition, the baseline of our study is CEM II with 17% GGBFS, unlike Iqbal's [24] CEM I with 0% GGBFS.

Furthermore, the carbonation rates can be calculated from Equation 7. In this study, they are 3.8, and 5.4 mm/year^{0.5} for ELC-17 and ELC-70, respectively. According to the Swiss standard SIA 262:1/2015, as cited in Moro & Cuchet[37], the natural carbonation rate can be calculated based on Equation 7:

$$K_N = b \times c \times K_S \quad (7)$$

where K_N is the natural carbonation rate (mm/year^{0.5}), b is the CO₂ volume percentage conversion factor ($\sqrt{\frac{0.04}{1.0}}$), c is a correction factor for accelerated carbonation (1.36). Based on Equation 7, the converted natural carbonation rates are 1.0 mm/year^{0.5} and 1.5 mm/year^{0.5} for ELC-17 and ELC-70, respectively.

These findings align with previous research investigating similar increases (~50 percentage points) in GGBFS replacement. Researchers [38] reported that the natural carbonation rate rose from approximately 2.5 mm/year^{0.5} to around 4 mm/year^{0.5}, an increase of roughly 60%, which closely matches the 50% increase observed between ELC-17 and ELC-70 in this study. Additionally, the accelerated carbonation rates at higher GGBFS contents reported in earlier studies further confirm that carbonation resistance generally decreases with increasing GGBFS content [18, 20].

This trend is particularly significant for reinforced concrete, because increased carbonation lowers the concrete alkalinity and can initiate reinforcement corrosion. At the same time, in plain concrete, carbonation can densify the cement matrix, leading to increased surface hardness and higher compressive strength [39].

4. DISCUSSION AND FUTURE RESEARCH

This study provides insights into the mechanical properties and carbonation resistance of concrete with varying replacement percentages of GGBFS. The compressive, direct tensile, and flexural tensile strengths varied among the specimens, and were mostly lower at higher GGBFS replacement levels at early ages of 7 and 28 days. However, at later ages, the high-GGBFS specimens showed mechanical properties like or even better than specimens with much lower GGBFS content.

In current construction standards, the compressive strength of concrete is typically evaluated at 28 days, which can lead to the rejection of high-GGBFS concretes that require more time to reach their full mechanical capacity. Extending the evaluation age to 56 or 91 days allows GGBFS-rich mixtures to leverage their latent hydraulic properties more effectively, thus delivering lower-carbon concrete solutions. However, it should be noted that longer curing periods can be impractical in many construction projects, as they drive up overall costs through extended financing and other overhead expenses. But longer curing, as was previously mentioned, has its benefits and it has also an effect on the long-term durability properties.

A more flexible approach to the typical 28-day strength requirement involves allowing certain construction tasks to proceed once the concrete has reached an adequate specified strength, rather

than waiting for its full 28-day or 91-day strength. While this strategy necessitates careful scheduling and robust safety checks, it can help minimize the idle time otherwise associated with slower strength development. Aligning the progress of construction tasks with actual, measured strength gains enables projects to retain the environmental advantages of high-GGBFS concretes while managing overall costs, as downtime is reduced, and resources can be deployed more efficiently.

An alternative route involves the use of environmentally friendly methods to accelerate early-age strength gain in high-GGBFS concretes, such as controlled heating with zero-carbon electricity or biofuels. While chemical accelerators also offer a means to speed up the setting and early strength development, they were intentionally excluded from this study to maintain a consistent baseline for comparison. It is worth noting that introducing such admixtures combined thermal curing could significantly enhance early-age performance but might have negative impacts on the durability of those concretes. This is especially important, given that in other studies [24, 20, 26] the higher replacement rates of GGBFS significantly deteriorate the frost resistance of concrete.

Building on the findings of this study, several future avenues are open for further investigations, such as:

- Examining the effect of combining GGBFS with other supplementary cementitious materials, such as fly ash, silica fume, and natural pozzolans.
- Exploring the use of GGBFS replacement ratios higher than 70 % with the use of both chemical accelerators and heated moulds or using water pipes for heating same way as cooling pipes are used. Pipes give even temperature to the concrete matrix and large temperature gradients can be avoided.
- Conducting field-based tests to validate laboratory findings under real construction conditions.

5. CONCLUSIONS

This research examined the mechanical performance and carbonation resistance of concretes prepared using high-GGBFS cements, specifically CEM III/A (42 % GGBFS) and CEM III/B (70 % GGBFS), comparing them against a reference CEM II/B-M (17 % GGBFS). Several mixes were produced and tested to evaluate the following mechanical properties: compressive, direct tensile, and flexural tensile strength, along with elastic modulus, Poisson's ratio, and carbonation resistance. The key conclusions are as follows.

- Compressive strengths of concretes made with CEM III/A and III/B can be as high or slightly higher than those made with CEM II/B-M, even at ages as early as 7 days, and especially at older ages of 91 and 182 days.
- At the age of 91 days, the flexural tensile strength of the CEM III mixes exceeded that of CEM II/B-M concretes. However, the 28-day flexural tensile strength was slightly (5 %) lower for CEM III/A and B concretes, when compared with CEM II/B-M concretes. These results suggest that flexural and compressive strength correlate similarly in concretes with high and low slag content.
- In this study, the direct tensile strength values of the CEM III/A and CEM III/B concretes were lower than those of CEM II/B-M, although all tested specimens met the target direct tensile strength. However, all tested specimens met the target direct tensile strength.

- The pull-off bond strength of both CEM III/A and B can be as high or higher than that of CEM II/B-M at ages of 91 and 182 days. On the other hand, at 28 days, concrete prepared with CEM II/B-M can have higher pull-off bond strength than those proportioned with CEM III/A or B.
- No major differences were found in the elastic properties of mixes proportioned with CEM III/B and CEM II/B-M, where the first had a slightly higher elastic modulus and Poisson's ratio. This suggests that conventional standardised calculations for structural design from EN 1992 may be used to estimate the mechanical functions of concretes made with CEM III/B. However, further research is needed to reach proper conclusions.
- After three months of accelerated carbonation testing in an environment containing 1 % CO₂ at a temperature of 21 ± 2°C, CEM III/B mixes showed a 50% higher calculated carbonation rate than that of CEM II/B-M mixes. The final carbonation depth of CEM III/B specimens was approximately 3.5 mm greater than those made with CEM II/B-M.

These conclusions show that the more sustainable CEM III/A and B are suitable replacements for CEM II/B-M in indoor structural applications where early strength or carbonation are not of critical importance.

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