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DURABILITY OF HIGH BELITE CEMENT AS NEW TECHNICAL SOLUTION FOR CONCRETE

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Abstract.

The study presents an investigation on the durability performance of concretes produced with an industrial scale high belite cement. This binder, thanks to the high amount of C-S-H gel and the lower C_3S/C_2S ratio, is characterized by high durability properties. Good resistance to freeze/thaw cycles, very low chloride migration and excellent resistance to sulfate attack were demonstrated. The accelerated carbonation test revealed that the belite cement, due to the high C_2S phase amount, is able to increase its strength over time when exposed to high CO_2 concentration. Durability and strength results were compared with those of CEM I, CEM II, and CEM III. In addition, a comparison of the performance of a self-compacting concrete produced with high belite cement and CEM I (as reference) is also presented. The results show that the self-compacting concrete with the high belite cement is able to reach sufficient strengths already after 1 day of hydration, with a low heat development and improved durability properties, compared to CEM I.

Keywords: Belitic cement, low heat cement, low heat concrete.

1. Introduction

New technical solutions aimed at building sustainable and durable structures need a synergy between the research on innovative binders, with reduced CO_2 emissions, and the development of the advanced concrete technology. Today, the use of supplementary cementitious materials (SCMs) is the main strategy to lower the environmental impact of the cement and concrete production. However, the long-term availability of fly-ash and slag will drop in the next future and has to be considered. While, limestone is the most used SCM being economic and widely available, but its use in concrete is an issue concerning durability requirements [1].

In this study, a High Belite Cement (HBC) is proposed as technical solution for concretes requiring low heat development and long service life. This type of binder is characterized by a reduction of CO_2 footprint around 8-10% when compared to conventional Portland cement, thanks toa reduced limestone demand as raw material and a lower burning temperature needed for clinker production.. The larger amount of C-S-H gel developed by the belite phase than alite is the basis to expect an improvement in durability performance, a possible driving force to move from Portland clinker to belite clinker or future blends with SCMs.

The HBC (4540 cm^2/g) used in this study was produced at industrial scale by Buzzi Unicem S.p.A. The C_2S content is higher than 54 wt.-% and the heat of hydration is lower than 227 J/g during 7 days. Performance and durability of the HBC were compared with those of CEM I 52.5N (3600 cm^2/g), , CEM II/B-LL 32.5R (5690 cm^2/g), and CEM III/A 52.5N LH (4150 cm^2/g), as references.

2. Results

2.1. Compressive strengths related to the heat of hydration

An undoubted advantage in the use of HBC is represented by its very low heat of hydration; in fact, as shown in Figure 1 it exhibits the lowest value between the different cements, also considerably lower than CEM III. This fact makes HBC highly interesting for mass concrete applications and for possible blends with Portland clinker and SCMs when low heat cement is required. Figure 1 shows also the comparison of the cements in terms of compressive strength, mortars were produced according to the EN 196-1 standard. After 1 day HBC develops a slightly lower compressive strength than CEM II, due to the slower hydration rate of the C_2S phase,and responsible for the low heat development. At 7 days the compressive strength of HBC and CEM II are almost comparable, while from 28 days on HBC exhibits higher results.

2.2. High Belite Cement for concrete at exposure classes XD, XS and XF

The concretes were produced according to the boundary conditions dictated in the German Institute for

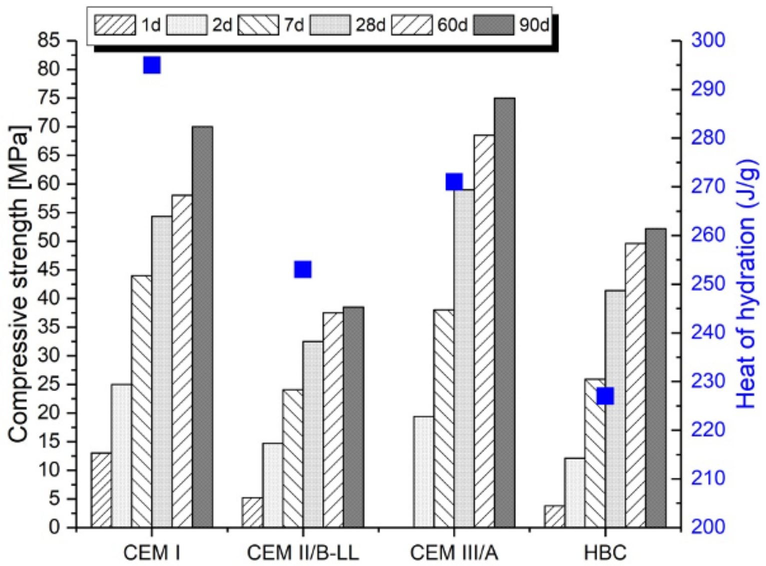

Figure 1. Comparison of the mortar compressive strength development correlated with the heat of hydration referred to the mass of cement.

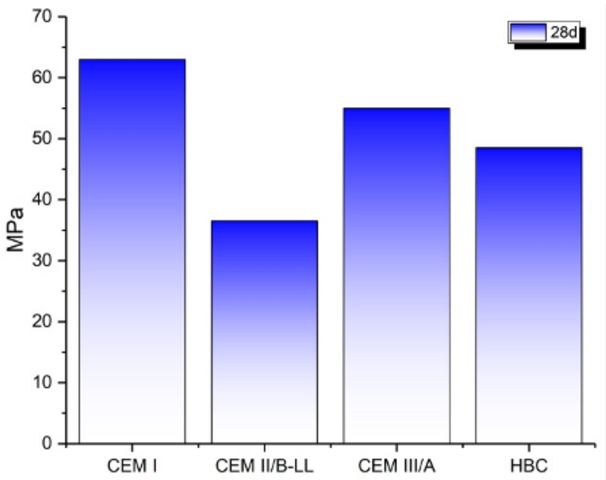

Figure 2. Compressive strength of the C1 concretes after 28 days of curing.

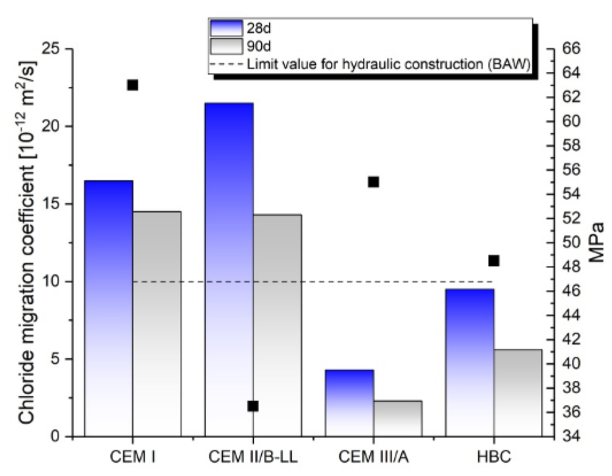

Figure 3. Chloride migration coefficients of C1 concretes. The solid square symbols show the compressive strength values at 28 days of hydration of mortars.

Construction Technology (DiBt) approval process for cements. Two concrete compositions were considered in this study. The resistance to chloride penetration, according to the BAW code of practice (similar to NT Built 192), was performed on concrete C1 produced by using Rhine gravel and sand with A16/B16 grading curve, 320 kg/m^3 of cement, and a w/c ratio of 0.5. No plasticizers were used in order to avoid their influence. Figure 2 shows the compressive strengths of concrete C1 produced with the different cements used at 28 days of curing; HBC shows exhibits a higher strength compared to CEM II, but lower than the other two cements.

The resistance to the freeze/thaw cycles immersed in 3% sodium chloride solution, according to the CDF method (DIN EN 12390-9), was instead performed on concrete C2 produced with: A16/B16 grading curve, 320 kg/m^3 of cement , a w/c ratio of 0.5, and an air void content of 4.5 ± 0.5 vol%.

As shown in Figure 3, HBC shows a higher resistance against chloride migration compared to CEM I and CEM II, but lower than CEM III. The migration coefficient of HBC is low enough for hydraulic engineering applications ($\leq 10 \times 10^{-12}$ m^2/s for XS1-2, XD1-2 or $\leq 5 \times 10^{-12}$ m^2/s for XS3 and XD3, in accordance with [2]).

Few information are reported in literature about the resistance of HBC to freeze/thaw cycles. The results, shown in the graph in Figure 4, reveal that HBC behaviour is comparable to that of CEM I; both cements are suitable for concrete applications with XF4 exposure class, presenting a scaling after 28 cycles lower than the threshold limit. On the contrary, both CEM II and CEM III show a weak resistance against

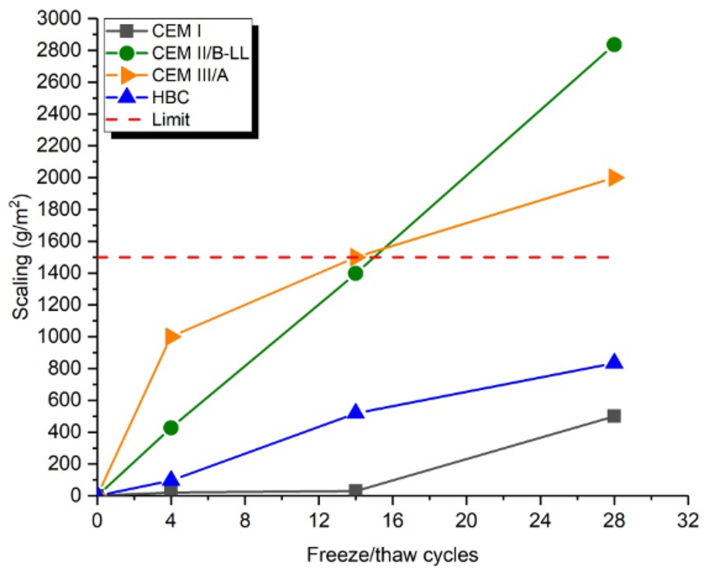

Figure 4. Resistance to freeze/thaw attack with deicing salt (CDF method).

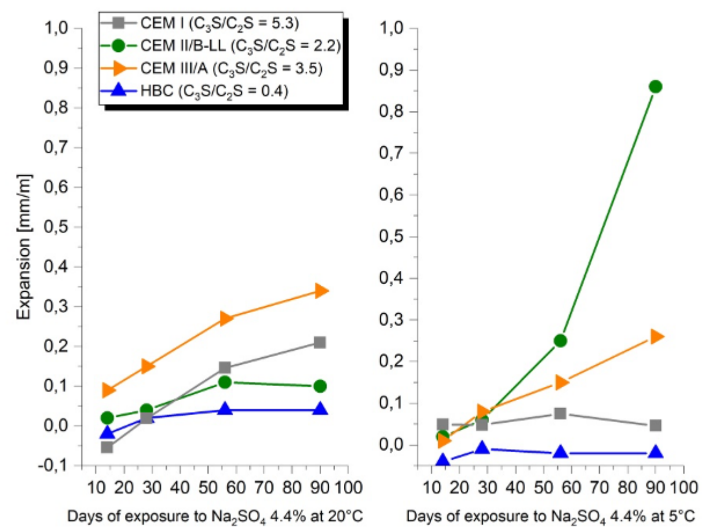

Figure 5. Expansion due to sulfate attack at 20 °C and 5 °C.

the stress induced by the 28 freeze/thaw cycles going beyond the threshold limit. These data confirm that the freeze/thaw resistance is a "weakness" property of limestone and slag cements, as well known.

The resistance to freeze/thaw cycles is often an obstacle to the implementation of sustainable binders with lower clinker factor.

2.3. Sulfate resistance

The sulfate resistance of the cements was tested according to the SVA flat prism (4 × 1 × 16 cm) method. The expansion of the prisms cured in a saturated $Ca(OH)_2$ solution was used as reference in order to evaluate the influence of sulfate attack at 20 °C and 5 °C. HBC has an excellent resistance against the aggression of sulfate, as confirmed by Sui et al. [3], and by the experimental results in Figure 5 where HBC exhibits the lowest expansion compared to the other cements. The resistance of Portland cement exposed to sulfate solution is related, in general, to the C_3A content, by the way a high amount of portlandite development can make concrete more vulnerable to sulfate attack, with the consequence formation of gypsum. The positive influence of the low C_3S/C_2S ratio (Figure 5), often not considered in the interpretation of the results, is a significant factor in the choice of a sulfate resistant cement [4]. The very high expansion of the CEM II at 5 °C is probably due to the formation of thaumasite [5].

2.4. Accelerated carbonation

In order to compare the depth of carbonation in the different cements considered, mortar samples were prepared in accordance with EN 196-1, stored in water up to 7 and 28 days, and then exposed to accelerated carbonation (chamber with 4% of CO_2 at 20 °C, and 70% RH) for 28, 56, 90, 140 days. The carbonation depth was determined at each due date with

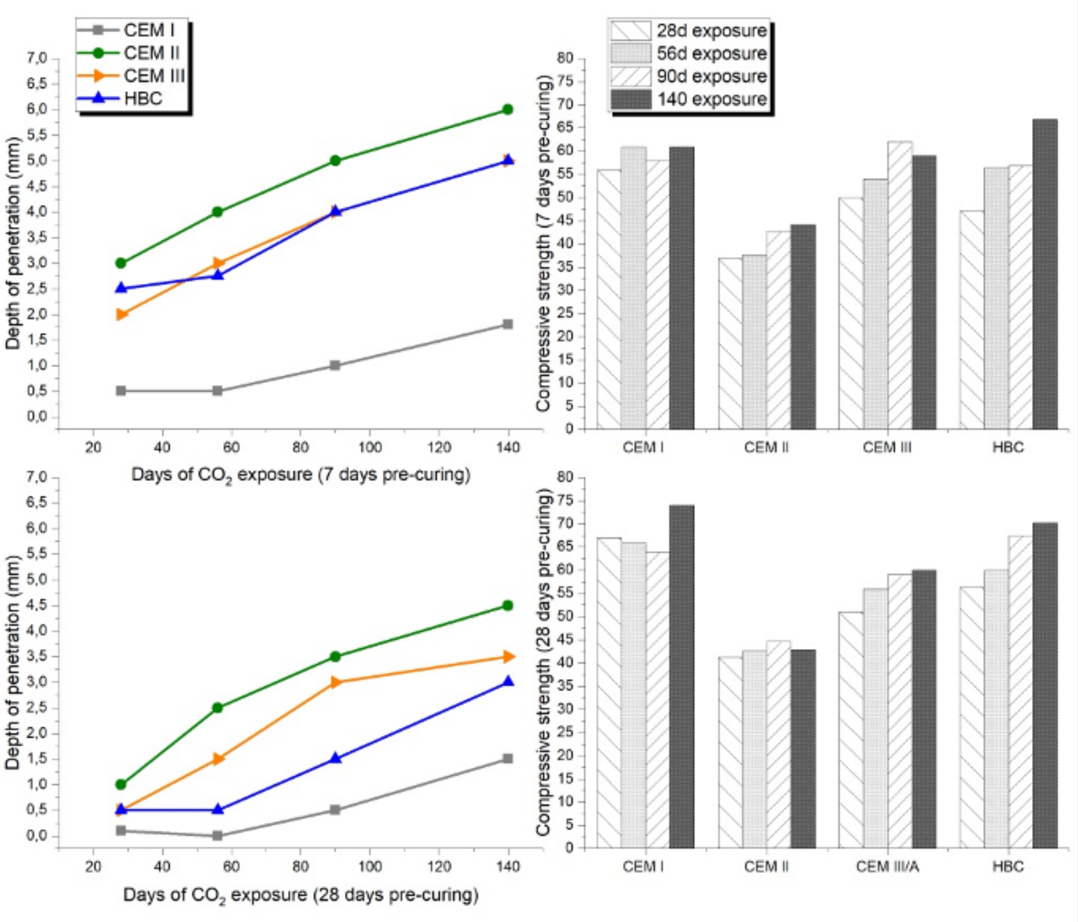

FIGURE 6. Accelerated carbonation (4% CO_2 at 20 °C, and 70% RH) and influence on the strength development.

the phenolphthalein test in accordance with RILEM recommendation. In addition, prior to determine the CO_2 penetration, on the same samples, compressive strengths were also evaluated to understand the effect of the belite content and the influence of carbonation curing on the physicochemical properties (Figure 6).

The carbonation-cured HBC has a significant growth in the compressive strength during the exposure time. Jang at al. [6] demonstrated that the CO_2 uptake capacity is proportional to the belite content and most of the belite phase is consumed by the carbonation reactions during the curing, resulting in the production of calcite. They observed that the carbonation curing of cement with high belite content leads to a more dense microstructure (with lower connected porosity) than those with high alite content. The hypothesis states that the carbonation reactions occurring at the inner layer of an unreacted belite particle are likely more rapid than that of the hydration reaction, resulting in the densification of the microstructure between the inner layer of C-S-H and the outer layer of unreacted belite particles, which significantly influences the strengths.

The depth of carbonation of HBC is proved to be strongly dependent on its grade of hydration, in fact when cured just for 7 days it is considerably higher than when it is cured for 28 days.

2.5. HIGH PERFORMANCE CONCRETE WITH HBC

A challenge in the application of HBC is represented by the slower strength development compared to conventional cements. Research on cement science is addressing efforts in order to overcome this barrier to the implementation. On the other hand, it must be said that in case of new eco-binders or innovative cements, not included in the standard EN 197-1, the evaluation of the performance considering standard mortars with a w/c of 0.5 (EN 196-1) could be not sufficient to explore their potential. On this purpose, progresses in concrete technology play a relevant role in order to match the needs of implementing eco-binders characterized by lower environmental impact with requirements on compressive strength, rheology and durability.

The behavior of a self-compacting concrete (SCC) with 420 kg/m^3 of HBC, 100 kg/m^3 of fly-ash, and a w/c ratio of 0.36 was compared with a SCC made with CEM I 52.5R, as reference.

The compressive strength of the HBC-SCC after 1 day reaches 20 MPa, and after 7 days is comparable to that of CEM I-SCC. HBC has also the great advantage of a very low heat of hydration. The durability of the two SCCs was evaluated in terms of freeze/thaw resistance and chloride penetration. The scaling due to freeze/thaw cycles (according to the CDF test) is in both cases very low: 450 g/m^2 for CEM I-SCC, and just 192 g/m^2 for HBC-SCC. The chloride migration of HBC-SCC is lower than that of CEM I-SCC, 2.2×10^{-12} m^2/s and 4.7×10^{-12} m^2/s, respectively.

3. Conclusions

The durability of concretes made with an industrially produced HBC was explored. The high resistance against chloride migration and freeze/thaw scaling of HBC, in comparison with CEM I, CEM II, and CEM III (as reference), were evaluated on concretes produced according to the boundary conditions dictated in the German Institute for Construction Technology (DiBt) approval process for cements.

HBC revealed to be suitable for exposure classes XS3, XD3 and XF4, thanks to its good resistance against freeze/thaw cycles, and its extraordinary ability to counteract the chloride penetration.

Almost no expansion was measured on HBC samples due to sulfate attack. The accelerated carbonation showed that HBC, thanks to the high amount of belite phase (higher than 54wt%), increases its compressive strengths during the CO_2 exposure. This interesting phenomenon needs to be deeply investigated at mineralogical and microstructural level, as well as the high durability properties of this cement related to the C-S-H gel formation. The durability of HBC is probably the main driving force for the future applications of this binder, together with its reduced environmental impact, and its low of heat of hydration.

The study also demonstrated that when formulated as self-compacting concrete, with low w/c, HBC can reach already after 1 day enough compressive strength (higher than 20 MPa) to work efficiently.

The potentialities of this binder need to be further explored also in blends with SCMs in order to develop sustainable and more durable future cementitious binders.

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