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Article:
Ambrose, J., Shenbagam, V.K., Guadagnini, M. et al. (2026) Durability testing for belitic calcium sulfoaluminate cement: equivalent hydration. Advances in Cement Research. pp. 1-9. ISSN: 0951-7197

https://doi.org/10.1680/jadcr.26.00014

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Durability testing for belitic calcium sulfoaluminate cement: Equivalent hydration

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ABSTRACT

The durability of calcium sulfoaluminate (CSA) cements is disputed in literature. The significant variance in CSA types and mix designs across studies lead to fundamental chemical differences, making direct comparisons untenable. In addition, standard protocols do not allow for sufficient time for belite hydration, thus leading to inaccurate assessments of the in-service performance of belite-rich cements. In this study, a commercial belitic CSA was used to produce samples under different curing conditions with the aim of achieving an 'equivalent hydration' comparable to that of a Portland cement cured for 28 days. Specimens were subsequently exposed to carbonation and elevated temperature (80 °C) for 1 year, after which their residual mechanical performance was evaluated.

It was found that when curing at 20 °C, an increased curing period of 91 days reduced depth of carbonation by approximately 35% and mitigated strength loss from exposure to elevated temperature by 10%. A similar improvement in performance was also observed when the curing temperature was increased to 40 °C for only 28 days.

These results, along with the general strength evolution observed for the tested specimens, indicate that ensuring a higher degree of hydration within curing protocols lead to improved long-term physical and mechanical performance.

Keywords

BCSA, equivalent hydration, durability, standards, carbonation, service life

1. Introduction

Calcium sulfoaluminate (CSA) based cements, and particularly high belite CSA (BCSA) cements are increasingly gaining attention as an alternative low-carbon binder. BCSA cements have ye'elimite as the primary reactive phase to rapidly harden to provide early-age strength, with belite contributing to later-age strength and improving durability, in a manner suspected to be akin to the high belite cements as described in Washa and Wendt, (1975). CSA-based cements have a notably lower carbon dioxide (CO_2) emission compared to conventional Portland cement (PC), mainly attributed to the lower clinkering temperatures, and the reduced limestone required for manufacturing (Hanein et al., 2018). These clinkers can be produced below 1300 °C, compared to the clinkering temperature of PC at 1450-1500 °C (Canbek and Erdoğan, 2020; Tan et al., 2020), thereby having a ~200 °C reduction in calcining temperature. The release of CO_2 due to decarbonation of the limestone is also reduced, with alite reported to release 0.58 g of CO_2 per g of clinker phase, whereas belite and ye'elimite can be expected to release 0.51 g and 0.216 g, respectively, which allows for a significant reduction in the overall CO_2 emissions when using ye'elimite over alite as the primary reactive phase (Afroughsabet et al., 2021; Aranda and De la Torre, 2013; Gartner, 2004). This results in a total estimated reduction of between 25 and 35%, dependant on the ye'elimite content.

In addition to environmental benefits, BCSA also has other highly attractive properties such as rapid hardening and shrinkage compensation, allowing for use in applications such as overnight repair of roads and airport runways, largely due to the rapid hydration of ye'elimite over the initial 24 hours (Bescher et al., 2019). Along with this, cements with high levels of belite continue to develop strength during their service life. This means BCSA can be an ideal material not only as a special cement (e.g., rapid repair) but also as a time saving general purpose cement, as it retains the high early strength properties of high-ye'elimite mixes, whilst there is potential for microstructure development and even self-repair (Acarturk et al., 2023; Gwon et al., 2019) over a long service life. There is potential for their use as general purpose cements, provided costs are reduced, for example by eliminating the requirement of bauxite (Shenbagam et al., 2025).

As will be further detailed in the materials section, the composition of the CSA cement used in this study comprises approximately 44 wt.% belite, 27 wt.% ye'elimite, 14 wt.% gypsum, and 15 wt.% of other phases, fitting into the BCSA category as seen in the nomenclature used in Ambrose et al., (2024); Bescher et al., (2019). It can be expected that when there is sufficient water and sulphate in a CSA system that the ye'elimite phase will be mostly reacted within 1 day (Bescher et al., 2019), producing a dense microstructure of ettringite (AFt). The minor amounts of amorphous aluminium hydroxide gel produced in this initial reaction will be consumed in the later reactions of belite to form strätlingite, followed by C-S-H, contributing to further strength development. Thus, the mechanical and long-term properties of BCSA cements are highly dependent on the stability of AFt in this time phase before belite reaction (Bescher et al., 2019; Cuberos et al., 2010), and how much belite reaction has occurred at the time of any

testing (i.e., how much the cement hydration chemistry has matured to mimic in-service scenarios).

Cementitious binders are conventionally tested after a 28-day curing period (BS EN 12390-10, 12). This duration is based upon assumption that a PC cement achieves over 80% of total hydration by this time (Scrivener et al., 2004) and thus will act as we expect an in-service sample to act. However, when the standards are used for alternative cements that contain high proportions of slower hydrating phases, the hydration degree at 28 days is rarely close to the high levels achieved by PC, and thus the testing protocol cannot be considered representative of an in-service system. Despite this, CSA tested in the literature will often display a good natural resistance to freeze-thaw, and with an ability to integrate admixtures of anti-freezes without reducing mechanical performance (Chen et al., 2024; Tan et al., 2020), presenting a strong case for use in cold environments. Furthermore, CSA-based cements have a reported superior resistance to chemical attack from sulphates, outperforming PC cements even when tested against CEM V (sulphate-resistant) cement (Bescher et al., 2016). However, as these non-conventional binders are not given sufficient time to fully develop their microstructure, many other tests performed at 28 days often severely underestimate their long-term performance. A revision of current standards through validated testing, as conducted in this work, is therefore necessary to adequately account for the distinctive hydration chemistries of different alternative binders.

As BCSA cements are typically used as a special cement for the repair of roads, bridges or airport runway/taxiways (Deo et al., 2022), they will be exposed to natural carbonation. In addition, as there is no alite in BCSAs the amount of CH in the hydrated system, which acts as a sacrificial mineral for carbonation in PC, is limited. As a result, the first mineral

to carbonate in CSA-based cements is ettringite, which will reprecipitate as crystalline calcite and gypsum (Yang et al., 2025). The pH range within which ettringite is stable has been reported in the literature to somewhat vary, with some studies suggesting values between 10.6–11, (Allahverdi and Škvára, 2000; Hassett et al., 1990; McCarthy et al., 1992), while others suggesting a much broader range of 9-13.4 (Day, 1992; Shimada and Young, 2004; Stark and Bollmann, 2000). Carbonation of the system will reduce the total pH, which could allow for further indirect destabilisation of AFt, thus affecting the performance of BCSA cement.

Many of these service conditions for CSA-based cements will put systems in situations that allow for heat build-up, with concretes known ability to absorb heat from solar insolation (Zhou et al., 2004), as many of the examples will be exposed to direct sunlight for all daylight hours. The needle structure of AFt has a high amount of bound H_2O molecules, at 32 per molecule, of which 23 molecules are reported to be loosely bound to the surface and very susceptible to loss (Perkins and Palmer, 1999). From work by Zhou and Glasser, (2001) it was shown that decomposition of ettringite occurs at higher temperatures, as the relative humidity increases. AFt can begin decomposition at 60 °C at a relative humidity of ~86%, where exceeding 70 °C will begin the process of large-scale ettringite decomposition. This means that in high-heat situations such as exposed pavement surfaces in summer, there is the very potential risk of causing ettringite breakdown and thus loss in strength.

This study therefore examines the performance of BCSA cement exposed to natural carbonation and elevated temperatures for up to one year. The role of curing (prolonged curing duration and elevated temperature) on hydration mechanisms is explored to establish an ‘equivalent hydration’ that will allow for belite hydration products to represent the in-service, long-term performance of the system.

2. Materials and methods

Samples in this study were prepared using a commercial belitic calcium sulfoaluminate cement (Rapid-Set^{TM}). Quantified X-ray diffraction (XRD) data of the same material were taken from Bescher et al., (2019), with β-C_2S accounting for 43.6 wt.% of the cement, α-C_2S 4.4 wt.%, ye'elimite 27.4 wt.%, anhydrite 10.6 wt.%, and bassanite 3.7 wt.%. Particle size analysis of the cement (Figure. 1) identified a distribution ranging from 0.1 to 100 µm, with most of the material falling within the 3–30 µm range. A sharp river sand, sieved to <2 mm, was used to prepare the mortar mixes. Samples of sand were assessed for water absorption before use, and appropriate corrections were made to the amount of required water for each of the test mixes. Filtered deionised (DI) water was used for all mixes to prevent contamination from minor elements.

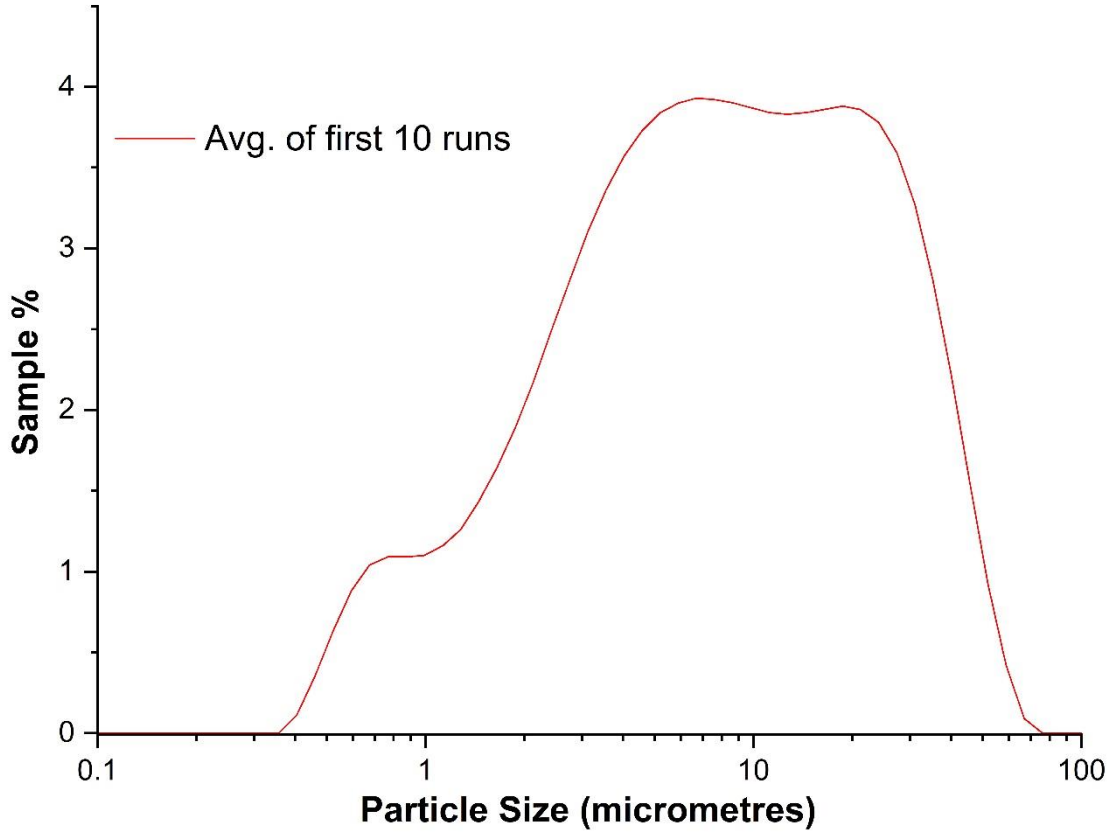

Figure. 1 Particle size analysis of the raw BCSA cement. All the particles lie between 0.1 and 100 microns, with a Dx (10) of 1.85µm, Dx (50) of 9.71µm, and a Dx (90) of 37.2µm.

All paste and mortar samples in this study were prepared with a w/c of 0.485, following from tested mix designs provided by the manufacturer. An overhead mixer was used for preparing paste samples, while a stand mixer was used for the mortar samples. Mortar samples were mixed in accordance with BS EN 12390-2, with a cement: sand ratio of 1: 2.75 and cured in sealed plastic bags sprayed with water to simulate ~100% RH, in environmental chambers set to either 20 °C or 40 °C. Samples to be exposed to carbonation were prepared as 160 x 40 x 40 mm prisms and tested in duplicate, and samples to be exposed to elevated temperatures as 50 mm cubes and tested in triplicate. The selection of specimen geometries was driven by the specific requirements of each test. Prisms were used for carbonation testing to facilitate splitting and the subsequent assessment of internal carbonation ingress. In contrast, elevated temperature testing focused primarily on loss of compressive strength, with no need for further analysis of the specimen post-test. Moulds were filled in two layers, with each layer being tamped and compacted before trowelling the top surface. All samples were demoulded 3 hours after mixing.

Paste samples were stored in vials, which were kept sealed with parafilm in an environmental chamber. The pastes samples were broken out of their vials after the desired times were reached, of 1, 7, 28, 91 and 365 days, then arrested using a solvent exchange method adapted from Snellings et al., (2018). The samples were ground using a pestle and mortar, passed through a 75 μm sieve, and subsequently tested in a Malvern Panalytical Aeris XRD under rotating reduced fluorescence between 5–80^{o} for 20 minutes.

Carbonation tests

After reaching their target curing duration of for either 28 or 91 days at 20 °C, or 28 days at 40 °C, the prism samples were transferred outdoors to undergo natural carbonation,

following a procedure adapted from EN 12390-10. Two conditions were assessed for carbonation, either 'covered', where samples were sheltered from direct rainfall and elevated to avoid pooling in accordance with the standard, or 'exposed', where samples remained uncovered and subject to natural precipitation.

The two exposure conditions were chosen to assess if there would be any change between samples tested in a more controlled environment, such as seen in (Afroughsabet et al., 2021) or how the material would perform in closer to in-service conditions, as seen in Deo et al., (2022) with these two studies recording significantly different performances. After the samples reached 1 year of exposure, 3-point bending tests were performed to assess their flexural strength. Flexural strength was tested here as it is a key requirement of the projects commonly using BCSA cement, i.e. overnight road repair. The tests were conducted in a Shimadzu universal testing machine with a capacity of 10 kN. The tests were performed in load control at a rate of 0.05 MPa/s (17.78 N/s) according to EN 12390-5. The fresh surfaces of the tested samples were then sprayed with phenolphthalein and an image analysis software, ImageJ (Schneider et al., 2012), was used to measure carbonation depth.

Elevated temperature tests

After curing for either 28 or 91 days at 20 °C or 40 °C, the 50 mm cube samples were weighed and transferred into an oven operating at a temperature of 80 °C. The weights of the samples were measured at regular intervals until weight stabilisation was reached, with additional occasional measurements taken throughout the exposure period. At the end of the 1-year period, the samples were weighed and subsequently tested to determine their compressive strength using a Shimadzu universal testing machine with a capacity of

300 kN. The tests were performed in load control at a rate of 0.5 MPa/sec (1250 N/s) according to EN 12390-3.

3. Results and discussion

3.1 Preliminary hydration data

The evolution of hydration in the mortar samples is expected to follow the trend seen in the XRD data obtained from the paste samples (Figure. 2). From these traces, it appears that belite hydration only begins to occur in samples cured at 20 °C from 91 days, with the main strätlingite peak appearing alongside the reduction in belite peaks from this point forward. This coincides with an increase in the monosulphate peak. Hence, a difference in the performance of the mortar samples cured for 91 days would be expected, as strätlingite is often attributed to the long term performance of binder systems (Andac and Glasser, 1999; Winnefeld and Lothenbach, 2010).

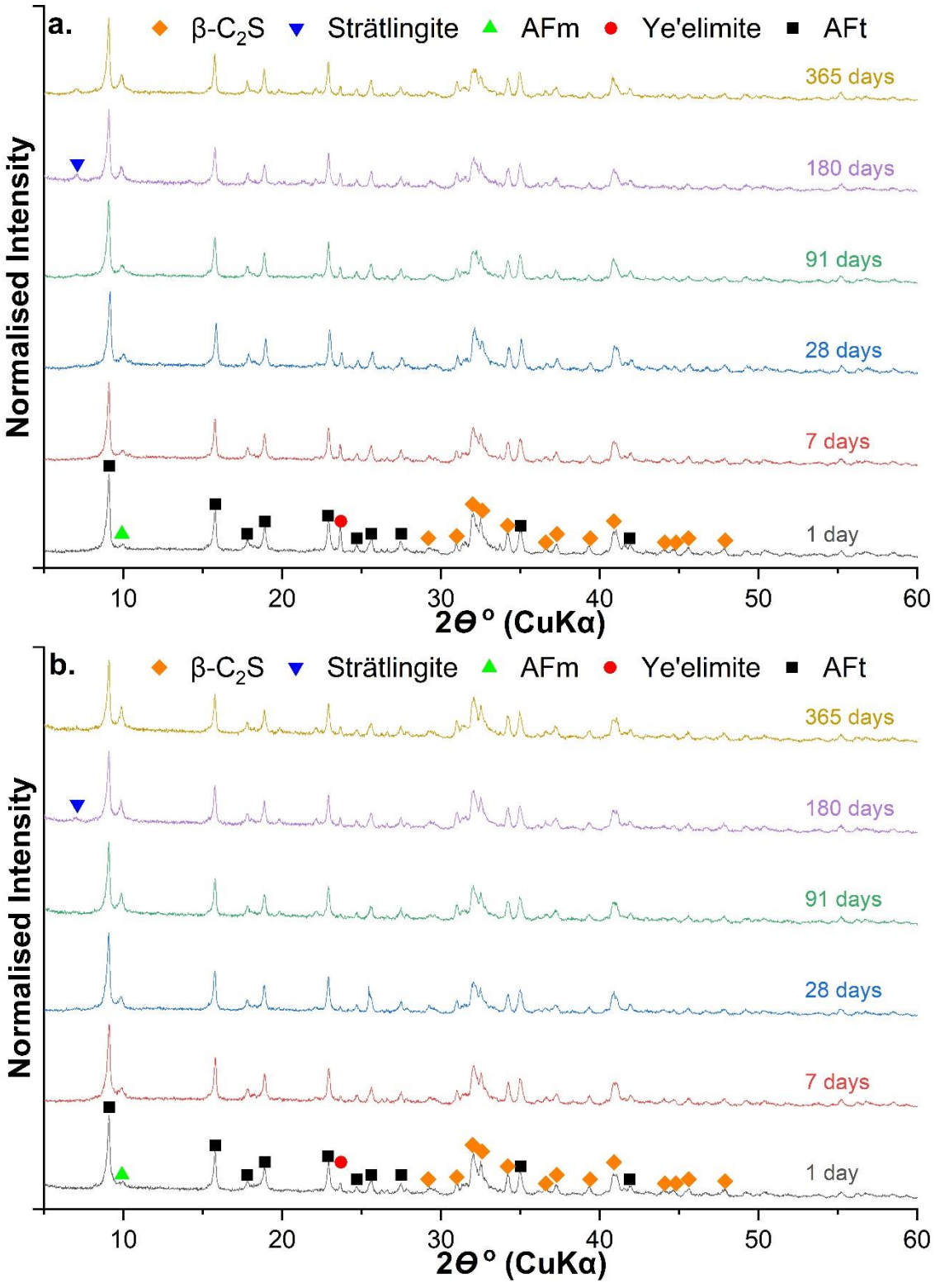

Figure. 2 The evolution of XRD traces of a 0.485w/c mix cured at 20 °C, **a.**, and 40 °C, **b.**, tested at significant time points. The evolution between 28 days and 91 days at 20 °C shows a significant strätlingite peak beginning to form. The strätlingite peak can be seen to develop earlier, from 28 days, when curing at 40 °C, but this appears to less intense when tested at 1 year compared to the 20 °C sample.

3.2 Natural carbonation of BCSA

3.2.1 Carbonation ingress

Before applying phenolphthalein, there were visible carbonation depths observed in several specimens (Figure 3.f), particularly the exposed samples, though this was also partially evident in the 40 °C samples cured for 28 days (not shown here). These visual boundaries in the samples could be attributed to the progression of carbonation and resulting decomposition of ettringite, as seen in works by Hargis et al., (2017) and Shenbagam et al., (2024), which directly alters the pore structure and water content in the hydrated matrix.

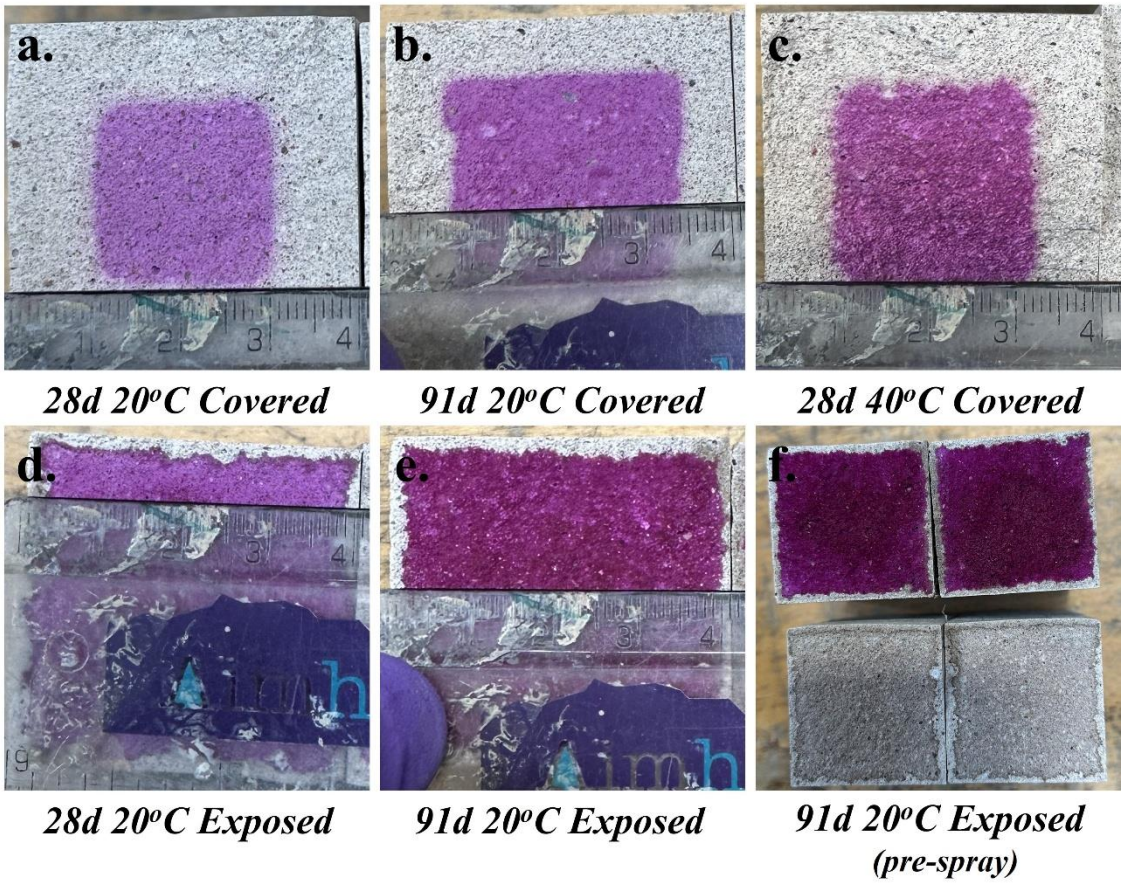

Figure. 3 Images taken immediately after splitting the samples and applying phenolphthalein. The large decrease in carbonation depth is visible between curing for 28 days (a, c and d) and 91 days (b and e). Carbonation depth for some samples was clear before applying the indicator, (f).

229 Carbonation ingress values for all tested samples are detailed in Table. 1. Specimens cured
230 at 20 °C for 28 days exhibited a large ingress of 10 mm after 1 year of exposure, indicating
231 poor carbonation resistance, while this reduced to 6.5 mm in specimens cured for 91 days.
232 A similar reduction in ingress was observed in samples cured at 40 °C for 28 days, which
233 exhibited a carbonation depth of 7 mm, showing an equivalent performance to that of
234 specimens cured for 91 days at 20 °C.
235 A significant difference in the level of carbonation ingress was also observed as a result
236 of exposure conditions, with the exposed samples always exhibiting a smaller carbonation
237 depth. Similar reductions in carbonation depth have been reported for exposed samples
238 of CSA-based cements, albeit of a differing chemical composition (Quillin, 2001)
239 comprising calcium sulfoaluminate cement (SAC) and ferroaluminate cement (FAC),
240 which are designated as 'third series' cement in China. However, carbonation depth did
241 not seem to be affected by the curing time when samples were exposed to rainfall
242 following an initial curing period at 20 °C. While characterisation of these samples could
243 not be performed, it is suspected that the wet conditions of the exposed samples facilitated
244 further hydration reaction of belite to take place, improving the original microstructure.
245 The water to cement ratio required for full hydration is estimated to be between 0.62 and
246 0.78 (García-Maté et al., 2013; Glasser and Zhang, 2000), suggesting that further
247 hydration may have occurred in these mortar samples during exposure (Tan et al., 2020;
248 Tang et al., 2015). This can also have caused the increase in strength of the samples
249 exposed to rainfall, Figure. 4. As this additional hydration took place after the initial
250 hardening and development of the microstructure, any new hydration product would have
251 helped reduce permeability, thereby reducing the ingress of CO_2. Further, the saturated
252 matrix likely inhibited the rate of CO_2 ingress.
253

Table. 1 Carbonation ingress and strengths of the samples left to naturally carbonate. ImageJ was used to measure remaining surface area of high pH, with ingress taken from the mean measured from 4 points taken immediately post applying phenolphthalein.

20°C 28 days 1 year Covered			
Carbonation ingress	10mm	**Surface area carbonated**	73.39%
Flexural strength	5.61 MPa	**Standard deviation**	0.49
20°C 91 days 1 year Covered			
Carbonation ingress	6.5mm	**Surface area carbonated**	55.57%
Flexural strength	6.66 MPa	**Standard deviation**	1.29
40°C 28 days 1 year Covered			
Carbonation ingress	7mm	**Surface area carbonated**	62.97%
Flexural strength	7.67 MPa	**Standard deviation**	0.44
20°C 28 days 1 year Exposed			
Carbonation ingress	2mm	**Surface area carbonated**	11.81%
Flexural strength	8.57 MPa	**Standard deviation**	0.06
20°C 91 days 1 year Exposed			
Carbonation ingress	2mm	**Surface area carbonated**	13.32%
Flexural strength	11.00 MPa	**Standard deviation**	0.39

3.2.2 Flexural strength

The samples cured at 20 °C for 28 days exhibited a slight reduction in flexural strength (approximately 12%) after exposure to covered natural carbonation, with the strength reducing from 6.37 MPa (at 28 days curing, before exposure) to 5.61 MPa (after 1 year exposure), as can be seen in Figure. 4 and Table. 2. On the contrary, the flexural strength of the exposed samples improved significantly (by approximately 35% from the 28 days strength), increasing to 8.57 MPa. Samples cured at 40 °C for 28 days only showed a minor loss in flexural strength (about 4%) after 1 year exposure to covered natural carbonation, with the strength reducing from 7.98 MPa to 7.67 MPa. Samples cured for 91 days showed a similar trend to those cured for 28 days, with a slight reduction in strength when exposed to covered natural carbonation for 1 year (~ 6%, from 7.05 MPa to 6.66 MPa), and a significant increase when left completely exposed.

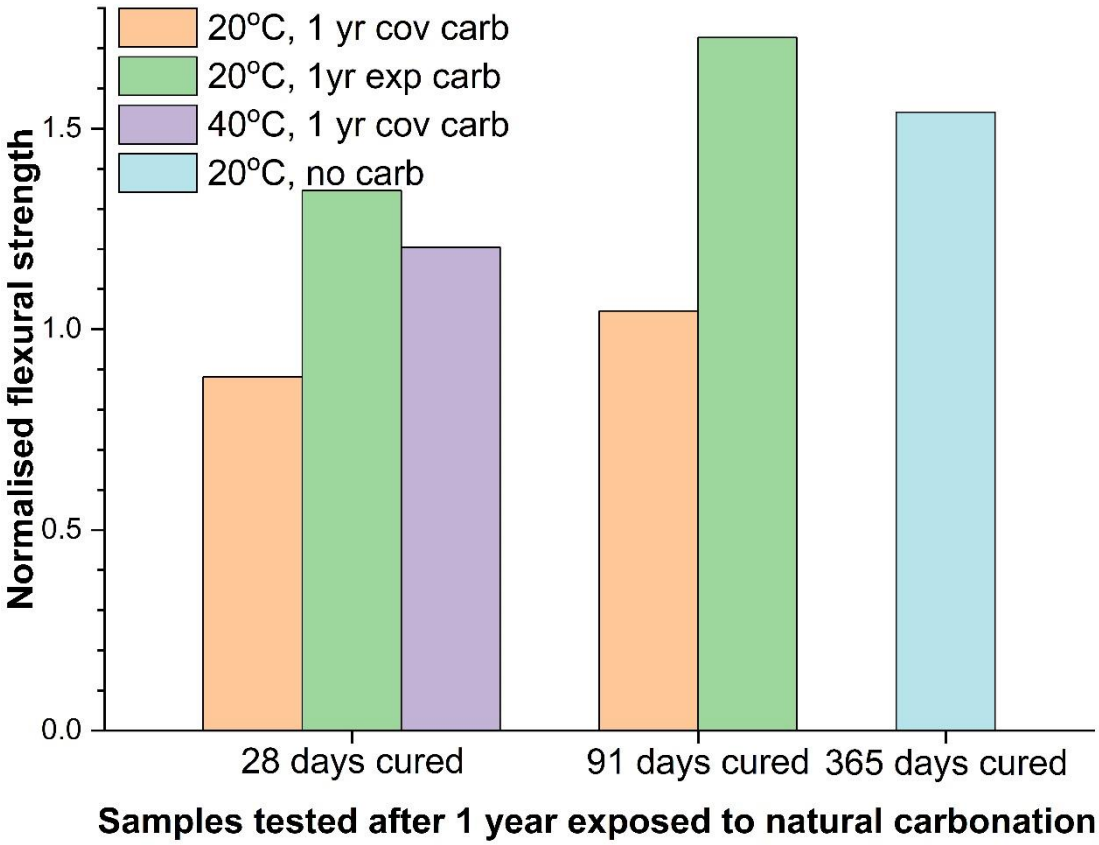

Figure. 4 Flexural strength of samples left to naturally carbonate, that are normalised to a sample cured for 28 days at 20 °C and then immediately tested without exposure to carbonation. A sample cured for 1 year and then immediately tested has also been included in the figure, to better display the effects of natural carbonation over curing conditions on strength evolution.

3.2.3 Discussion

Ambrose et al., (2024) discussed the disparity reported in the literature between the performance of a CSA sample tested for carbonation after 180 days in laboratory conditions (from Afroughsabet et al., (2021)), and a BCSA sample taken from Seattle-Tacoma airport after 23 years of emplacement (Deo et al., (2022)). This disparity was attributed primarily to the significant chemical differences between the two CSA-based binders, with the CSA sample having little belite, and thus the microstructure subjected to carbonation consisted predominantly of ettringite, with little influence from the hydration products of belite; particularly strätlingite and C-S-H. However, as seen in

Table. 1 and Table. 2, it can be seen that exposure conditions also have a significant impact upon the carbonation resistance and mechanical performance, and presumably hydration, of the samples. A purely mechanical explanation for this increase in performance is that the infilling of pores with rainwater creates a barrier, thus forcing CO_2 to first dissolve into the pore water before it can carbonate the sample. A chemical explanation is that the addition of pore water post curing acts as additional free water, allowing any unreacted belite to hydrate and producing strätlingite and C-S-H, thus improving the microstructure over the year. Likely both are in play, particularly when considering the significant strength differences between exposed and covered samples. While TGA and XRD of samples are necessary to definitively identify the underlying mechanisms, phenolphthalein contamination necessitated disposal of the sample after initial testing. Future studies should include the preparation of separate paste samples, exposed to the same conditions, to facilitate the necessary characterisation.

Regardless of the underlying causes, the results clearly indicate that the performance of samples under 1 year of in-service UK conditions can differ significantly from that of samples subjected to the carbonation procedures prescribed in EN 12390-10, and thus the true usefulness of the standard comes into question. The large variance may be attributed to several factors, most notably the difference in moisture content between samples that were fully exposed to rainfall, similarly to the exposed samples in this study and those reported in Deo et al., (2022), and those that were kept in more controlled conditions, such as the covered samples in this study and those reported in Afroughsabet et al., (2021). Through the lens of 'equivalent hydration', it becomes clear that by pivoting away from using the standard curing age of 28 days, as specified in EN 12390-10, a significant difference in carbonation performance can be observed, with samples cured for 91 days both exhibiting enhanced carbonation resistance and strength over their

counterparts. These findings support the introduction of a critical step before performing any characterisation of alternative binders. By monitoring total reaction over time, an equivalent curing condition that results in at least 80% of the expected total hydration can be identified and specified for comparative testing.

Table. 2 Flexural strengths of samples tested immediately after curing, and then after being left to carbonate for 1 year in natural conditions. The change in strength between these samples, and a sample cured for 1 year, has been calculated.

Sample (20 °C)	Strength post cure (MPa)	Strength post carbonation (MPa)	Change (±%)	1 yr cure sample strength (MPa)	Change (±%)
28d Cov	6.37	5.61	-11.93	9.82	-42.87
28d Exp		8.57	+34.54		-12.73
91d Cov	7.05	6.66	-5.53		-32.18
91d Exp		11.00	+56.03		+12.02
40°C 28d Cov	7.98	7.67	-3.88	*Not Tested*	

3.3 Exposure to elevated temperatures

Figure. 5 presents the normalised mass loss of samples, expressed as a percentage of the demoulded sample weight. This plot clearly demonstrates the immediate loss incurred during the curing process, particularly for samples cured for 91 days at 40 °C, which exhibited the greatest initial weight loss of 4.75% (decreasing from 259.2 to 246.9 g). However, despite this initial larger loss, both samples cured at 40 °C retained a higher percentage of their initial mass compared to those cured at 20 °C after one year of conditioning at 80 °C. A smaller difference in mass loss is observed between the samples cured for 91 days. This can indicate a greater degree of reaction, and consequently less free pore water available for additional loss over the conditioning period, or the formation of more stable hydration products over the extended curing time.

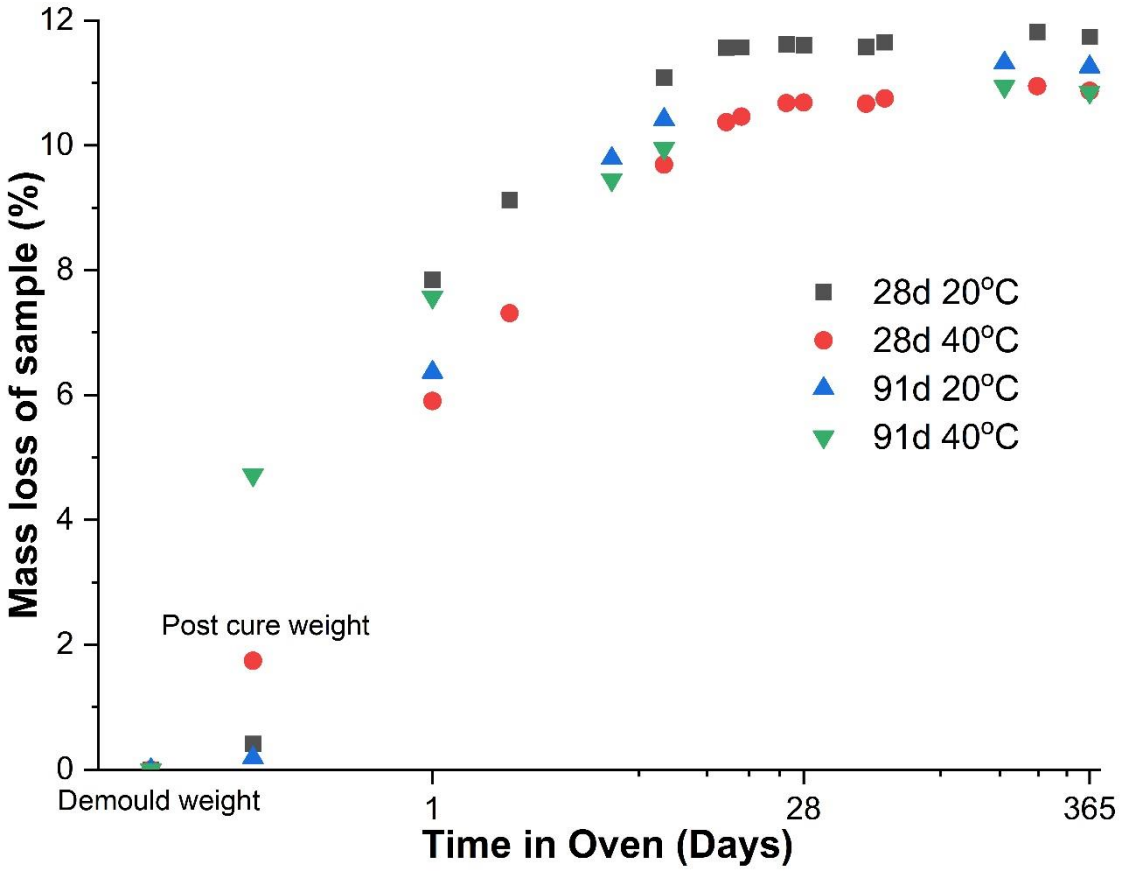

Figure. 5 Mass loss evolution of the tested samples. Samples cured at 40 °C display less total weight loss than those cured at 20 °C, though there is a reduction in loss when curing for 91 days.

After one year of conditioning the samples underwent final weighing, and their compressional strength was determined (Table. 3) to better quantify the effects of thermal exposure on mechanical performance. The strengths of samples cured at 20 °C and 40 °C for one year has also been included (Table. 3), to allow for direct comparison of the effect of curing and exposure to elevated temperature. Figure. 6 presents the compression strength of the conditioned samples normalised to the strength value of their companion reference sample after the initial curing period. The most significant strength loss was observed in the samples cured at 20 °C for 28 days and at 40 °C for 91 days. The other two samples, cured for 28 days at 40 °C, and 91 days at 20 °C, retain the highest strengths,

of 45.68 MPa, and 45.89 MPa, respectively, as well as having low levels of strength loss. The major loss in strength when curing for 28 days at 20 °C can be primarily attributed to the lack of total hydration, and subsequent halting of hydration once transferred to the oven. The loss in strength for the sample cured for 91 days could indicate an instability of later stage belite hydration products at 40 °C in BCSA, which may lead to early accelerated curing and result in poorer long-term strength, especially over extended curing periods. Thus, the preferred curing duration at 40 °C should be limited to 28 days to prevent compromising long-term performance.

Table. 3 Compressive strengths of samples tested immediately after curing, and then after being left exposed to high temperature in the 80 °C oven. The loss in strength between these samples, and to those cured for 1 year and tested, has been calculated.

Sample	Strength post cure (MPa)	Strength post oven (MPa)	Loss (%)	1yr cure samples strength (MPa)	Loss (%)
20C 28d	42.39	30.74	*28.48*	61.30	*49.85*
20C 91d	56.47	45.89	*18.74*		*25.14*
40C 28d	50.84	45.68	*10.15*	53.07	*13.93*
40C 91d	65.74	43.48	*33.86*		*36.20*

Future studies should utilise prism specimens for elevated temperature testing, as the resulting halves from flexural tests can subsequently be used for compression testing. This approach would allow for a more robust evaluation of the relationship and variance between flexural and compressive strength. In addition, carbonation tests on heat-treated samples would provide valuable insight into the chemical evolution triggered by thermal exposure.

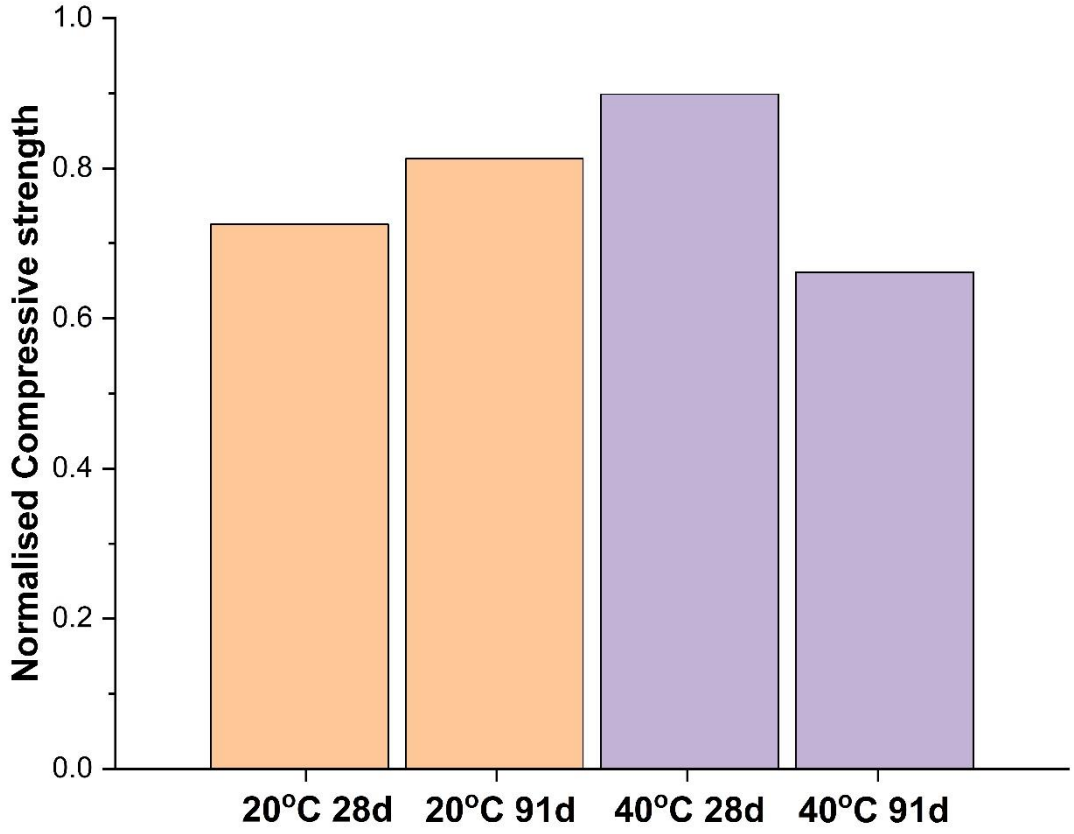

Figure. 6 Compressive strengths of samples cured to the shown conditions and then exposed to elevated temperatures (80 °C) for one year, normalised to the compressive strength of samples tested after curing at 20 °C for 28 days.

4. Conclusions

The data presented in this paper support the feasibility of achieving 'equivalent hydration' through the implementation of different curing protocols (prolonging the curing duration or increasing the curing temperature). While further research is needed, it is shown that curing for 91 days at 20 °C produced samples with significant improvements to samples cured for 28 days in both natural carbonation resistance, with ingress reduced by ~35%, from a depth of 10 mm to 6.5 mm, and elevated temperature stability, with strength loss reduced by ~34.8%. It is also shown that curing for 91 days at 20 °C produces samples with comparable long-term performance to samples cured for 28 days at 40 °C

(accelerated hydration), in terms of both exposure to natural carbonation and elevated temperatures, where these two sets of variables were the best performing across the study.

From the analysis of the data presented above, it is also evident that the carbonation protocols recommended in EN 12390-10 may not provide a representative assessment of the performance of structures exposed to typical in-service conditions, with samples performing significantly better when exposed to rainfall. This can be attributed to the resulting increase in pore water content, which can lead to an increased late-stage hydration of belite, with subsequent microstructure refinement, and/or the need for the CO_2 to dissolve into the pore solution before reaction can occur with the solid phases.

In future studies, companion paste samples should be produced and exposed to the same conditions as the mortar specimens. Whilst the mortar samples are used for physical testing, the paste samples can be used to characterise and identify any phase changes within the binder.

Regardless, a sample exposed to 1 year cycle in a typical UK climate can be expected to perform significantly better than that left exposed to laboratory conditions.

Acknowledgements

This work is funded by a UKRI Future Leaders Fellowships (MR/V023829/1) and (MR/V023829/2), “Green, Circular, and Smart Cement Manufacture”. The authors would like to thank all the advisory board members for their insights and guidance. We specifically thank Éric Bescher and CTS cement manufacturing Co, for providing us with the BCSA cement used for the study. We also would like to acknowledge and thank Lucy Ellwood for supporting with the collection of PSD data.

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