Cement & Concrete Composites 35 (2013) 163–170

Contents lists available at SciVerse ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Compressive strength development of calcium aluminate cement–GGBFS blends

Önder Kırca [a], İ. Özgür Yaman [b,*], Mustafa Tokyay [b]

[a] ÇimSA Çimento San. ve Tic. A.Ş., Mersin, Turkey
[b] Department of Civil Engineering, Middle East Technical University, Ankara, Turkey

ARTICLE INFO

Article history:
Received 6 March 2011
Received in revised form 10 March 2012
Accepted 19 August 2012
Available online 27 August 2012

Keywords:
Calcium aluminate cement
Ground granulated blast furnace slag
Conversion

ABSTRACT

The compressive strength development of calcium aluminate cement (CAC) and ground granulated blast furnace slag (GGBFS) blends that were subjected to different curing regimes are investigated. The blends had GGBFS/CAC ratios between 0% and 80%, by mass. Mortar specimens, prepared with a water:binder:sand ratio of 1:2:6, were subjected to seven different curing regimes and the compressive strengths were monitored up to 210 days. In order to understand the effect of temperature on compressive strength development, XRD analyses were also conducted on paste specimens of CAC–GGBFS blends at 28 and 210 days. The experimental analysis results revealed that in CAC–GGBFS combinations, particularly where GGBFS was the main constituent, the formation of stable straetlingite (C_2ASH_8) instead of calcium aluminate hydrates hindered the unwanted conversion reactions.

1. Introduction

Calcium aluminate cement (CAC) is an inorganic hydraulic binder whose properties are mainly dominated by monocalciumaluminates [1,2]. One of the most important property of calcium aluminate cement is its rapid hardening characteristic, particularly within the first 6 h. Owing to its rapid strength development, CAC was used in structural applications, but its use in load-carrying systems later became very limited, after the failures of structures in several countries. It was then realized that CAC type binders can go through a series of conversion processes causing a substantial strength loss in the hardened product which caused the failure of those structures [3].

In previous studies, it was pointed out that during the hydration of CAC at low temperatures (<27 °C) the common hydration products that would occur are CAH_{10}, C_2AH_8, and AH_3 [1–6]. C_3AH_6 cannot be observed at low temperatures, unless conversion of CAH_{10} and C_2AH_8 to C_3AH_6 occurs over time. The rate of conversion is determined to be time dependent and complete conversion may take several years, particularly at temperatures lower than 20 °C. Moreover, as the curing temperature increases, the conversion occurs more rapidly. Conversion is directly related with strength, since with the conversion of unstable CAH_{10} and C_2AH_8 to stable C_3AH_6, some water is released causing an increase in porosity and therefore a reduction in strength [3,7,8]. It was also mentioned by other researchers that the bonds of C_3AH_6 and AH_3 are weaker than those of CAH_{10} and C_2AH_8, even at equal porosity [3–5].

Therefore, some precautions have been considered to eliminate or decrease the harmful effects of conversion. These attempts mainly focused on blending CAC with other inorganic materials, such as pozzolanic admixtures. Through blending CAC with other materials, inorganic cementitious systems with special properties such as fast setting, rapid hardening, high early strength and shrinkage compensation may be attained.

The addition of ground granulated blast furnace slag in a CAC system is reported to change the hydration mechanism of a CAC system. Previous studies have demonstrated that, in CAC–GGBFS blends of suitable ratios, there may be no conversion even at elevated temperatures, even though various types of CAC with different alumina contents were utilized [9–17]. For instance, Quillin et al. [9] worked on a CAC with an alumina content of 40% and reported that the modified chemistry of hydration caused by the high silica content of the GGBFS addition prevents conversion of CAC–GGBFS blends. On the other hand Heikal worked on CAC with an alumina content of 53% [16,17] together with air-cooled and water-cooled slags. It was reported that calcium aluminates, in the presence of moisture, react with amorphous silica of GGBFS to form C_2ASH_8, known as straetlingite or gehlenite hydrate. Due to the high stability of the compound, CAC–GGBFS blends, even if they were kept at elevated temperatures for a prolonged period of time, do not exhibit any loss in compressive strength that would occur in a pure CAC system [13,16–18].

The objective of this study was to investigate and quantitatively evaluate the effects of time, temperature and GGBFS amount on the compressive strength development of CAC–GGBFS blends. For this purpose mortar specimens were prepared using five different CAC–GGBFS blends and the compressive strengths were determined up to 210 days. Moreover, X-ray diffraction (XRD) analyses

---

* Corresponding author. Tel.: +90 312 2105473; fax: +90 312 2105401.
E-mail address: ioyaman@metu.edu.tr (İ. Özgür Yaman).

0958-9465/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cemconcomp.2012.08.016

Table 1
Properties of CAC and GGBFS.

	CAC	GGBFS
Chemical analysis (%)		
CaO	37.6	37.16
SiO_2	2.2	35.94
Al_2O_3	40.1	12.06
Fe_2O_3	17.1	0.64
MgO	0.84	7.59
SO_3	0	2.29
K_2O	0.03	1.16
Na_2O	0	0.4
Loss on ignition	0	0
Physical properties		
Specific surface area (cm^2/gr)	3290	4420
Median size (μm)	17.9	9.38
Mechanical properties		
Compressive strength at		
6 h	41.1	–
24 h	63.2	–
28 days	85.1	–
Flexural strength at		
6 h	5.5	–
24 h	8.2	–
28 days	9.1	–

of the hydrated pastes were carried out at 28 and 210 days to observe the differences between different curing temperatures and regimes.

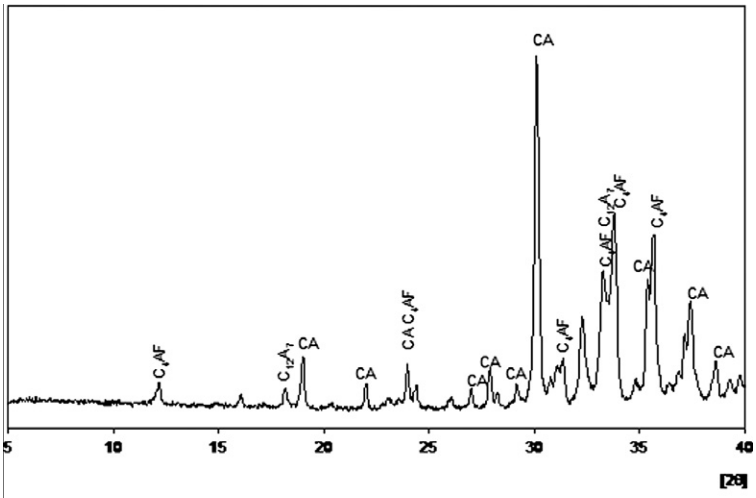
2. Experimental program

2.1. Materials

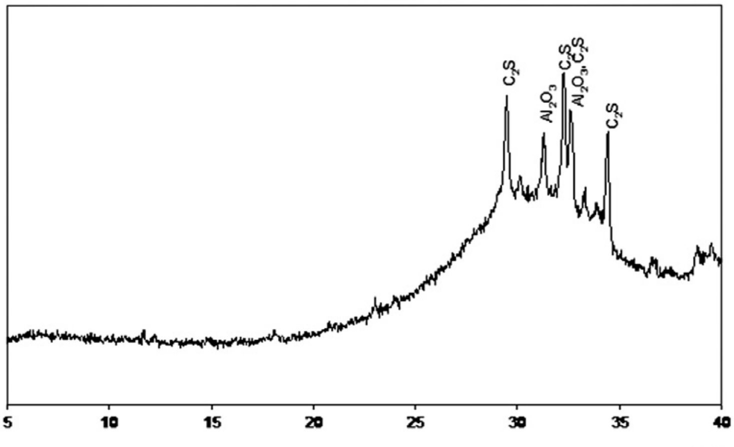
CAC was produced by ÇimSA Cement Production and Trade Co. with a brand name of ISIDAÇ 40, and contained an alumina content of 40%. GGBFS, a by-product of the steel industry, was supplied by Iskenderun Steel Co. Chemical and physical properties of CAC and GGBFS are given in Table 1, together with the mechanical properties of CAC as determined by its relevant standard, prEN 14647 [2].

The mineralogical composition of CAC and GGBFS were determined by XRD analyses. As seen in Fig. 1a, CAC is mainly composed of CA, $C_{12}A_7$, and C_4AF compounds. The amorphous or poorly crystalline structure of GGBFS, presented in Fig. 1b, makes the identification of existing minerals difficult. However, dicalciumsilicate and alumina peaks were observed.

Within the scope of the experimental program, five different CAC–GGBFS blends were produced where, 0%, 20%, 40%, 60%, 80%,



(a) CAC



(b) GGBFS

Fig. 1. XRD analysis of CAC and GGBFS.

Table 2
Compressive strength of CAC–GGBFS blends cured continuously at the same temperature. (Compressive strengths are given in MPa.)

Day	Curing temperature (°C)																			
	20 GGBFS amount (%)					30 GGBFS amount (%)					40 GGBFS amount (%)					50 GGBFS amount (%)				
	0	20	40	60	80	0	20	40	60	80	0	20	40	60	80	0	20	40	60	80
3 h	5.2	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	31.7	14.0	11.2	∗	∗
6 h	42.1	16.8	15.5	6.6	2.0	∗	∗	∗	∗	∗	34.1	15.7	11.0	3.7		26.6	26.1	16.4	7.8	∗
12 h	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	23.2	21.5	16.2	9.5	5.1
1	60.5	58.6	39.3	17.4	3.8	49.9	46.6	27.6	13.2	6.4	27.2	25.1	19.3	12.6	8.2	21.7	21.9	17.5	12.5	7.8
2	65.9	58.8	40.8	179	100	38.0	45 6	27.6	15.2	103	25.5	95 3	93 1	185	98	22.8	26.2	19.8	143	81
3	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	23.7	29.1	22.7	15.3	11.2
4	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	23.7	27.9	30.6	26.0	12.3	22.8	31.2	24.3	15.5	13.7
5	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	22.0	32.6	26.2	18.0	17.0
6	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	27.1	33.7	32.7	27.1	19.9	∗	∗	∗	∗	∗
7	80.4	63.2	39.6	27.3	11.4	28.3	49.2	32.8	32.9	12.2	∗	∗	∗	∗	∗	28.0	35.8	28.2	20.3	19.1
8	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	26.2	35.3	36.1	28.4	21.4	∗	∗	∗	∗	∗
10	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	26.7	38.0	38.5	29.5	23.7	∗	∗	∗	∗	∗
12	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	26.5	37.5	38.0	28.9	25.2	∗	∗	∗	∗	∗
14	∗	∗	∗	∗	∗	24.3	44.4	44.2	35.7	24.6	27.0	40.5	39.4	31.0	25.8	∗	∗	∗	∗	∗
16	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	26.9	39.9	39.4	31.3	27.2	∗	∗	∗	∗	∗
18	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	27.7	41.5	41.3	32.2	28.1	∗	∗	∗	∗	∗
20	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	25.9	42.2	40.3	31.1	28.8	∗	∗	∗	∗	∗
21	∗	∗	∗	∗	∗	23.9	39.4	49.6	42.5	32.8	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
28	85.6	73.5	53.6	38.8	25.7	22.9	46.4	50.8	46.0	36.2	26.3	45.0	41.4	32.9	30.9	27.8	41.1	33.3	24.4	28.5
35	∗	∗	∗	∗	∗	27.8	42.7	53.6	52.2	39.6	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
42	∗	∗	∗	∗	∗	28.4	42.2	54.4	56.8	41.2	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
49	∗	∗	∗	∗	∗	28.9	36.6	55.1	59.1	42.4	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
56	∗	∗	∗	∗	∗	27.7	36.1	55.0	60.1	42.5	26.8	45.6	44.4	39.1	37.4	29.1	42.5	34.5	29.1	33.6
60	78.7	74.3	59.2	53.3	32.2	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
63	∗	∗	∗	∗	∗	25.4	36.0	57.7	60.0	44.2	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
70	∗	∗	∗	∗	∗	22.7	36.1	57.6	62.1	45.0	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
77	∗	∗	∗	∗	∗	26.4	35.2	57.8	63.1	45.5	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
84	∗	∗	∗	∗	∗	25.5	36.0	60.3	63.7	47.7	27.6	42.9	43.5	40.1	35.0	29.6	44.0	37.1	31.8	35.2
90	76.3	74.4	66.8	60.1	37.0	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
91	∗	∗	∗	∗	∗	25.0	36.0	60.5	65.1	45.0	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
98	∗	∗	∗	∗	∗	29.0	44.2	61.7	64.8	44.7	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
112	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	28.1	48.0	48.2	45.0	41.4	30.7	45.8	39.8	33.2	36.7
119	∗	∗	∗	∗	∗	25.6	49.9	57.1	65.7	43.6	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
120	75.9	64.2	73.7	63.7	43.1	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
133	∗	∗	∗	∗	∗	23.8	50.0	58.5	63.2	44.2	27.9	49.8	49.6	45.5	42.6	∗	∗	∗	∗	∗
150	79.6	71.2	75.5	67.3	48.6	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
154	∗	∗	∗	∗	∗	25.0	50.7	59.3	65.6	45.7	27.4	49.9	50.3	48.5	43.5	29.7	44.8	39.6	35.0	38.3
180	75.9	74.8	76.3	68.2	47.4	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
182	∗	∗	∗	∗	∗	24.6	52.5	60.6	67.9	45.6	27.9	49.1	48.1	50.1	43.5	∗	∗	∗	∗	∗
210	71.5	73.1	77.5	68.4	51.8	26.2	52.3	61.0	68.2	49.4	28.5	50.2	49.9	51.4	43.9	30.6	44.9	41.7	35.1	40.1

∗Test were not conducted at these ages.

by mass, of CAC was replaced by GGBFS. These blends were then used to prepare mortar and paste specimens that would be used for compressive strength and XRD analysis, respectively.

2.2. Curing regimes

In order to investigate the effects of curing temperature on CAC–GGBFS blends, mortar and paste samples were prepared with a constant water–binder ratio of 0.50 and were subjected to seven different curing regimes in water. The curing regimes are designated as follows:

- 20 °C, 30 °C, 40 °C, 50 °C (specimens were subjected to these temperatures up to 210 days).
- 20–30 °C, 20–40 °C, 20–50 °C (specimens were subjected to 20 °C for the first 28 days, and then to 30 °C, 40 °C, and 50 °C for the remaining 182 days).

2.3. Compressive strength tests

The compressive strength of CAC–GGBFS blends were determined through mortar mixtures of 450 g CAC–GGBFS blend, 1350 g CEN standard sand and 225 g water as outlined by EN 196-1 [19]. Six specimens were used to determine the compressive strength at the end of each specified age for each curing regime.

2.4. XRD analysis

XRD analysis of hydrated paste samples were conducted using a Phillips PW-660 diffractometer with a Cu Kα radiation. At 28 and 210 days, the paste samples for XRD analysis were taken out of water, air-dried, and were crushed and ground so that whole sample passes the 90 μm sieve. 5 g sample was obtained by quartering method and pellet specimens were prepared. For each pellet specimen, scanning was performed between 5° and 30° with a 2θ increment of 0.05°.

3. Discussion of test results

The results of the strength tests are summarized in Tables 2 and 3. Table 2 presents the strength test results of all mixtures with GGBFS replacement ratios of 0–80% by CAC and cured continuously at 20 °C, 30 °C, 40 °C, and 50 °C. On the other hand, Table 3 shows the results of all mixtures cured 28 days at 20 °C and then at elevated curing temperatures of 30 °C, 40 °C, and 50 °C. As the conversion process is presumed to occur earlier at higher temperatures, the ages that

Table 3
Compressive strength of CAC–GGBFS blends cured at elevated temperatures subsequent to an initial curing temperature of 20 °**C** for 28 days. (Compressive strengths are given in MPa.)

Day	Curing temperature (°C)																			
	20GGBFS amount (%)					30 GGBFS amount (%)					40 GGBFS amount (%)					50 GGBFS amount (%)				
	0	20	40	60	80	0	20	40	60	80	0	20	40	60	80	0	20	40	60	80
28.5	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	67.4	66.1	48.0	40.2	28.2
29	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	62.2	56.0	47.8	43.6	31.0
29.5	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	54.9	45.7	47.4	44.5	31.8
30	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	73.7	63.0	50.6	43.4	30.9	39.5	30.7	47.6	46.1	33.1
30.5	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	29.2	29.2	48.3	50.0	34.5
31	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	21.2	28.5	47.8	50.2	35.1
31.5	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	20.4	28.8	49.7	52.4	35.1
32	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	65.1	60.5	50.5	48.1	33.9	18.4	29.8	49.4	52.3	37.9
32.5	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	19.3	30.4	50.1	52.4	37.7
33	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	18.4	31.5	52.5	55.9	38.7
33.5	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	18.7	31.4	52.4	56.0	38.9
34	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	62.0	49.4	49.9	50.2	35.5	∗	∗	∗	∗	∗
35	∗	∗	∗	∗	∗	79.9	72.3	54.1	48.1	33.7	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
36	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	51.9	46.3	51.2	55.5	35.9	∗	∗	∗	∗	∗
38	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	46.6	37.9	53.9	55.4	39.4	∗	∗	∗	∗	∗
40	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	51.1	33.8	54.6	59.7	41.6	∗	∗	∗	∗	∗
42	∗	∗	∗	∗	∗	76.7	67.6	57.2	54.2	38.0	47.7	32.6	58.2	61.3	41.3	∗	∗	∗	∗	∗
44	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	40.2	33.4	56.4	60.9	41.6	∗	∗	∗	∗	∗
46	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	37.4	32.3	57.7	61.3	43.6	∗	∗	∗	∗	∗
48	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	35.0	35.6	61.0	63.2	43.4	∗	∗	∗	∗	∗
49	∗	∗	∗	∗	∗	73.2	67.6	62.8	60.0	40.5	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
50	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	29.4	35.3	60.2	62.9	43.7	∗	∗	∗	∗	∗
52	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	28.5	35.1	59.6	63.0	43.9	∗	∗	∗	∗	∗
54	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	23.9	37.2	61.8	62.4	44.5	∗	∗	∗	∗	∗
56	∗	∗	∗	∗	∗	70.7	73.9	63.3	60.2	40.4	18.8	39.4	63.4	64.6	45.3	20.7	44.6	64.8	63.9	42.5
60	78.7	74.3	59.2	53.3	32.2	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
63	∗	∗	∗	∗	∗	68.3	63.0	68.8	63.2	43.2	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
70	∗	∗	∗	∗	∗	65.4	61.1	69.1	63.4	43.9	19.7	41.1	64.1	65.0	45.6	∗	∗	∗	∗	∗
77	∗	∗	∗	∗	∗	66.0	66.8	71.0	65.6	43.5	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
84	∗	∗	∗	∗	∗	64.6	58.4	71.0	65.6	47.0	19.6	42.9	63.5	65.1	45.0	21.4	45.2	68.0	66.7	45.6
90	76.3	74.4	66.8	60.1	37	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
91	∗	∗	∗	∗	∗	63.1	51.4	70.4	66.7	47.3	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
98	∗	∗	∗	∗	∗	62.0	52.2	69.5	67.5	48.2	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
112	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	20.0	43.7	68.2	66.6	49.2	22.4	45.1	68.0	68.5	50.0
119	∗	∗	∗	∗	∗	56.8	39.8	73.4	66.5	44.9	20.4	43.6	69.6	70.2	46.7	∗	∗	∗	∗	∗
120	75.9	64.2	73.7	63.7	43.1	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
133	∗	∗	∗	∗	∗	58.4	33.8	69.8	67.9	44.4	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
150	79.6	71.2	75.5	67.3	48.6	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
154	∗	∗	∗	∗	∗	46.3	37 0	72.9	68 5	46 4	21.5	44 7	71.8	69 1	49 9	22.8	45 0	69.6	72.00	48.2
180	75.9	74.8	76.3	68.2	47.4	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗	∗
182	∗	∗	∗	∗	∗	46.8	35 3	73.6	70 3	50 0	22.1	45 3	74.9	69.1	49 8	∗	∗	∗	∗	∗
210	71.5	73.1	77.5	68.4	51.8	41.6	35.7	74.3	71.7	49.5	21.4	43.3	73.4	70.2	57.6	24.3	49.2	75.7	74.7	54.2

∗Test were not conducted at these ages.

the strengths are determined were selected accordingly. For example, the specimens cured at elevated temperatures such as 50 °C were tested more frequently within the first week, whereas the specimens cured at 20 °C were tested more frequently at later ages.

3.1. Pure CAC mixture

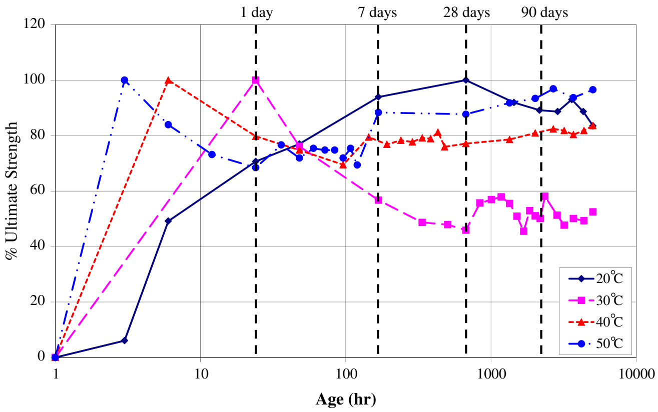
It can be seen from Table 2 that curing at 20 °C results in a continuous increase in strength up to 28 days when 85.6 MPa was reached. In order to visually examine the data, Fig. 2 is prepared. In that figure the strength at each age is normalized by the ultimate strength of the mixture cured at that particular curing regime. Now it is clear from the figure that the ultimate strength is reached at 28 days when the mix is cured at 20 °C with a slight reduction in strength at later ages. At 30 °C, 40 °C and 50 °C, however, the maximum strengths are 49.9 MPa, 34.1 MPa, and 31.7 MPa, which are attained at 24 h, 6 h and 3 h, respectively. The time to reach the maximum strength is reduced with increasing temperature as clearly observed in Fig. 2a. At later ages, there is again a slight reduction in the strength of specimens cured at 30 °C. However, the strength of specimens cured at 40 °C and 50 °C do not change significantly.

Upon increasing the temperature from 20 °C to 30, 40, and 50 °C after 28 days, the strength reduction is much more pronounced reaching of about 75% for 50 °C as presented in Fig. 2b. Therefore, it is clear that the curing temperature has a significant impact on strength development of pure CAC mixtures.

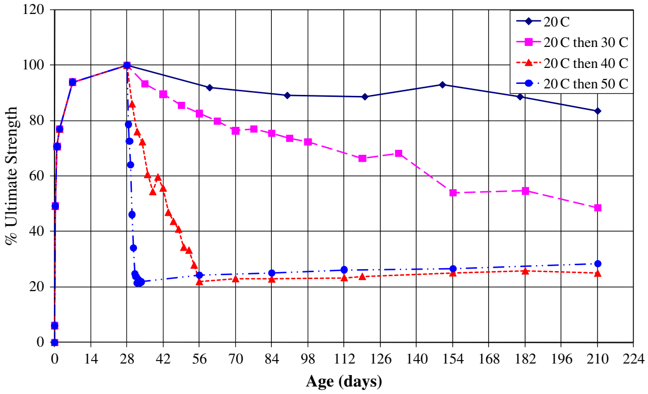
As can be seen from the X-ray spectra of the pure CAC paste provided in Fig. 3, common hydration products observed at 28 days and at 210 days are C_3AH_6 and AH_3, at all curing regimes. On the other hand, formation of CAH_{10} is observed only at 20 °C which is not stable at higher temperatures. Similar conclusions were also drawn in previous studies [1–4,16,17,20–26].

3.2. CAC–GGBFS blends

When the compressive strength development of the mixture with a GGBFS amount of 20% subjected to a curing temperature of 20 °C is considered (Table 2), it can be seen that a compressive strength of 73.5 MPa is reached at the end of 28 days with no significant change in the compressive strength at 210 days. When the data is analyzed graphically, it is clear that when cured continuously at 30 °C, 40 °C and 50 °C, the mixtures had a steady improvement in strength and the ultimate strength of mixtures were

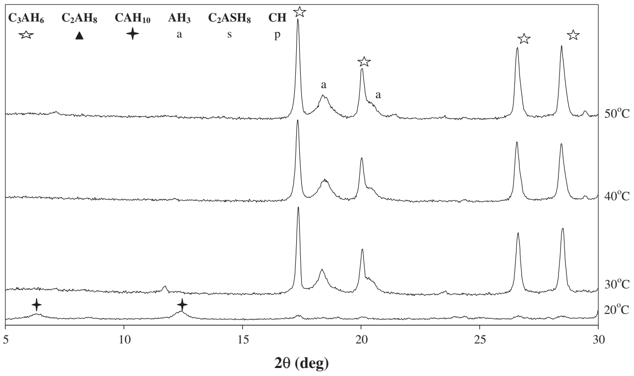


(a) Cured at constant temperature

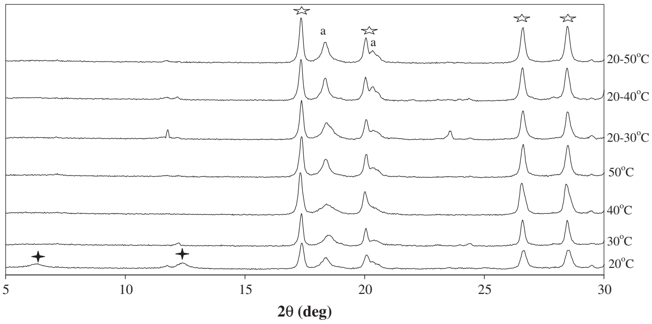


(b) Cured initially at 20 °C and later at elevated temperatures

Fig. 2. Compressive strength development of CAC.

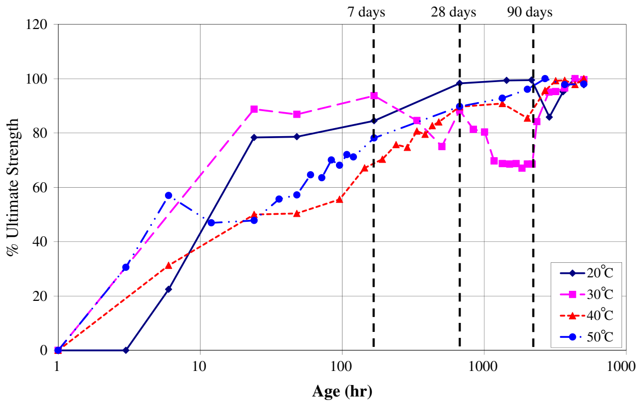


(a) at 28 days

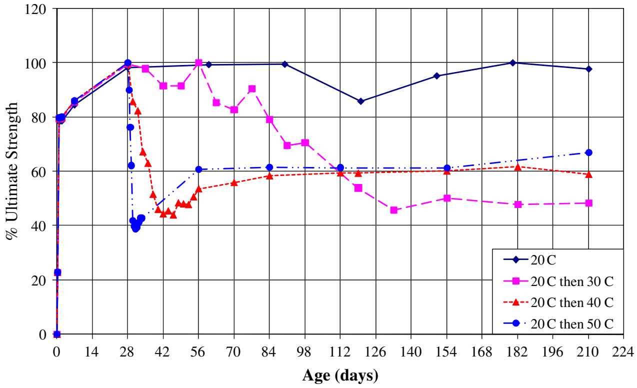


(b) at 210 days

Fig. 3. XRD patterns of the CAC for different curing regimes.

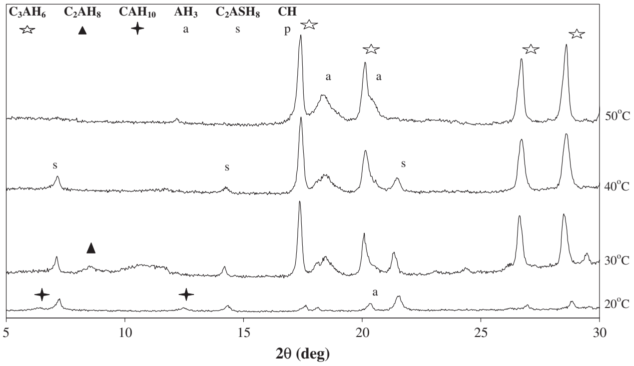


(a) Cured at constant temperature

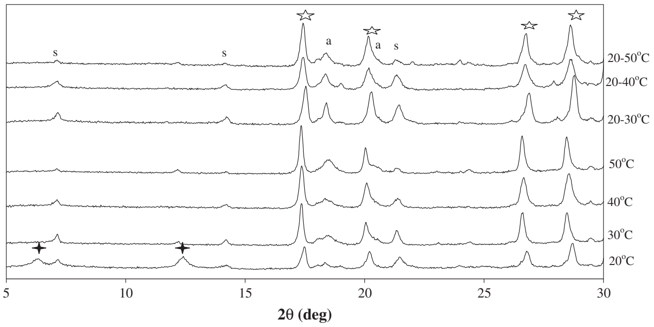


(b) Cured initially at 20 °C and later at elevated temperatures

Fig. 4. Compressive strength development of CAC with 20% GGBFS replacement.



(a) at 28 days



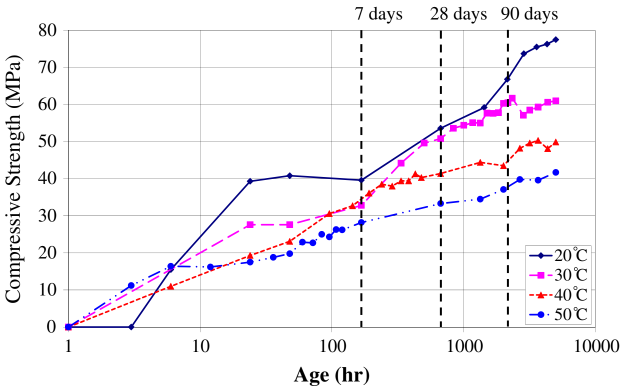
(b) at 210 days

Fig. 5. XRD patterns of the CAC with 20% GGBFS replacement for different curing regimes.

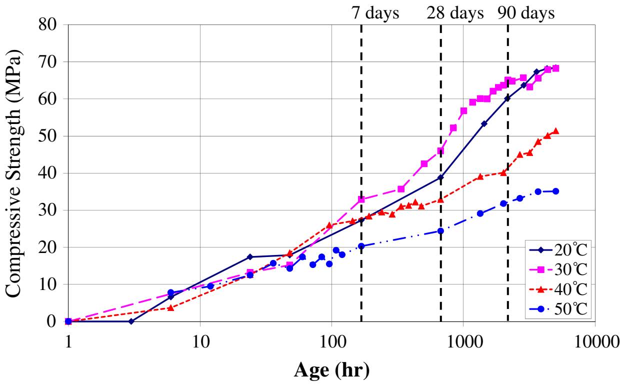
reached at 210 days no matter what the curing temperature was (Fig. 4a). On the other hand, as the curing temperature is increased after 28 days, the strength of the mixtures again dropped, however not as significant as the pure CAC, as presented in Fig. 4b. When the X-ray spectra of this blend's paste presented in Fig. 5 are examined, besides the peaks of the pure CAC paste, the straetlingite (C_2ASH_8) peak is also observed in most of the curing temperatures. The straetlingite presumably occurs as a result of the reactions between the silica of the GGBFS and calcium aluminates of the CAC.

Inclusion of GGBFS in CAC, above 40% changed the hydration mechanism of the CAC system, substantially. As seen in Fig. 6, mixtures prepared with 40%, 60% and 80% replacement levels exhibited a progressive strength improvement with time when cured continuously at 30 °C, 40 °C and 50 °C. There was no strength reduction within 210 days of curing no matter what the curing temperature was. This is mainly due to the formation of stable straetlingite instead of C_3AH_6. For example, as can be observed from the X-ray spectra of the mixtures with 40% replacement levels presented in Fig. 7, these mixtures had CAH_{10} at 28 days when cured at 20 °C. However, CAH_{10} is converted partially to C_3AH_6 but mostly to straetlingite up to 210 days, as there is no CAH_{10} at that age. Therefore, the strength reduction due to the conversion of CAH_{10} to C_3AH_6, is compensated by straetlingite formation, and thus the strength progressively increased. Another important observation related with straetlingite formation is that the higher the curing temperature, the less was the straetlingite formation and the more was C_3AH_6. Particularly at 50 °C, the formation of C_3AH_6 was faster than that of straetlingite and therefore C_3AH_6 could not be replaced by straetlingite, completely. This was also consistent with the strength development curves presented in Fig. 6. The lowest strengths were observed under continuous curing at 50 °C, since conversion itself (or formation of C_3AH_6) causes an increase in porosity, and thus strength reduction [3–5].

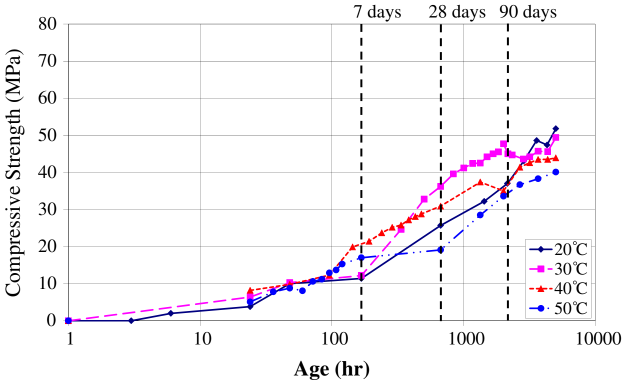
Another way of looking at the effect of GGBFS amount and curing temperature is to plot the increase in compressive strength beyond 28 days, by dividing the ultimate strength to 28 day strength, as presented in Fig. 8. It is clear from the figure that as the amount of GGBFS in the blend increases the strength of the mixture increases beyond 28 days depending on the curing temperature. For the pure CAC mixture cured at 20 °C, there was a 20% reduction in strength beyond 28 days. As the GGBFS addition increased, the strength reduction turn into strength gain and at a replacement level of 80%, there was a strength gain of about 50% beyond 28 days. It can be observed from the figure that for GGBFS replacement amounts over 40% the ultimate strength increased over 25–50%. Therefore, it can be concluded that concretes made by pure CAC are prone to a reduction in compressive strength under particularly hot climatic conditions due to conversion reactions. However, CAC–GGBFS blends exhibit no strength reductions, they even show strength improvements, under the same climatic conditions, as long as a proper CAC/GGBFS ratio is chosen.



(a) 40% GGBFS replacement level



(b) 60% GGBFS replacement level



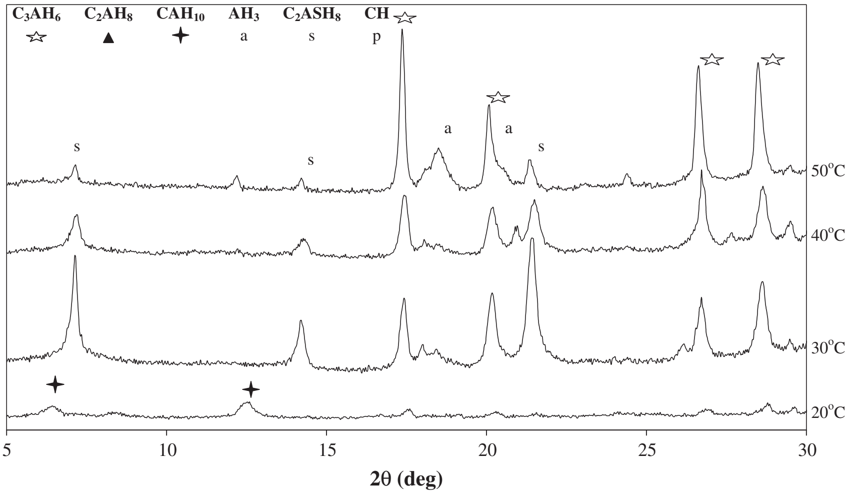
(c) 80% GGBFS replacement level

Fig. 6. Compressive strength development of CAC–GGBFS blends cured continuously at the same temperature.

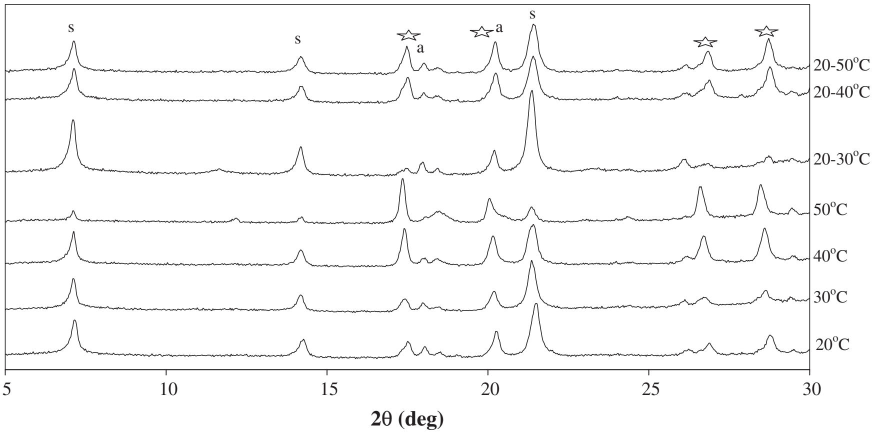
4. Conclusion

The following conclusions were drawn from this experimental investigation:

1. Pure CAC specimens cured at low temperatures experienced a continuous strength improvement up to a peak strength level followed by a drastic strength reduction until a residual strength level, where conversion was completely finished. However, when cured at higher temperatures, they showed a steady strength improvement up to a similar residual strength level, without experiencing an initial peak strength. Therefore, the ultimate compressive strength or residual strength of all pure CAC specimens, even though they were cured at different temperatures, coincided or would coincide within the same range of 20–30 MPa.
2. The conversion duration of pure CAC specimens at low temperatures was longer compared to the ones cured at elevated temperatures. In addition, curing initially at low temperatures followed by a high temperature curing resulted in a longer conversion duration compared to the ones cured continuously at elevated temperatures.
3. In CAC–GGBFS blends, particularly where GGBFS ratio was higher than 40%, the formation of stable straetlingite (C_2ASH_8) instead of calcium aluminate hydrates hindered the probable conversion reactions, without causing a strength reduction.



(a) at 28 days



(b) at 210 days

Fig. 7. XRD patterns at 40% GGBFS replacement level for different curing regimes.

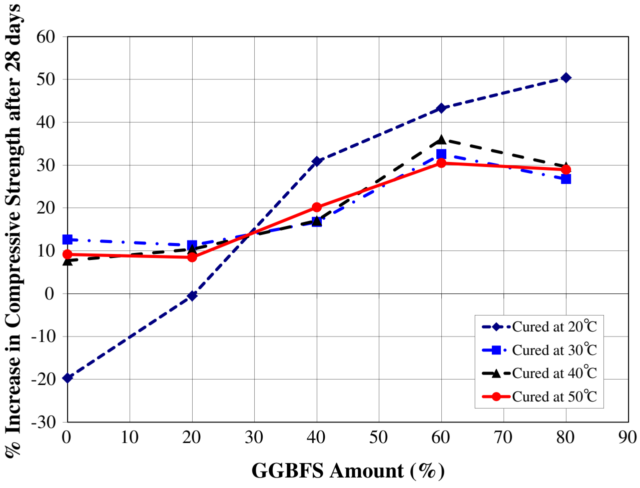


Fig. 8. Effects of curing temperature and GGBFS amount on the ultimate strength of GGBFS–CAC blend.

The strengths of these blends continued to increase beyond 28 days exceeding 75 MPa for 40% replacement levels cured at 20 °C.

4. The formation of stable straetlingite instead of calcium aluminate hydrates was dominant at temperatures below 40 °C. At higher temperatures, C_3AH_6 formed more rapidly than straetlingite, causing about 40–50% lesser ultimate strengths when compared to the blends cured at 20 °C.

References

[1] CEN/TC 51 N 645. Report of CEN/TC 51 WG 6 TG1: calcium aluminate cement. Krakow; 2000.
[2] CEN/TC 51 N802, prEN 14647. Calcium aluminate cement: composition, specifications and conformity criteria. Lisbon; 2004.
[3] Odler I. Special inorganic cements. New York: E and FN Spoon Publication; 2000.
[4] Andion LG, Garces P, Cases P, Andreu CG, Galao O. Metallic corrosion of steel embedded in calcium aluminate cement mortars. In: Proceedings of the international conference on CAC, Edinburgh, UK; 2001. p. 405–21.
[5] Lamour VHR, Monteiro PJM, Scrivener KL, Fryda H. Mechanical properties of calcium aluminate cement concretes. In: Proceedings of the international conference on CAC, Edinburgh, UK; 2001. p. 199–213.
[6] Midgley HG, Midgley A. The conversion of high alumina cement. Mag Concr Res 1975;27:59–77.
[7] Fryda H, Scrivener KL, Chanvillard G, Feron C. Relevance of laboratory tests to field applications of calcium aluminate cement concretes. In: Proceedings of the international conference on CAC, Edinburgh, UK; 2001. p. 227–46.
[8] Garsel DV. High alumina cements and chemical binders. Seminar given by Alcoa Industrial Chemicals Europe at Institute of Refractories Engineering. South Africa; 1996.

[9] Quillin KC, Osborne G, Majumdar A, Singh B. Effects of W/C ratio and curing conditions on Strength development in BRECEM concretes. Cem Concr Res 2001;31:627–32.

[10] Majumdar AJ, Singh B. Properties of some blended high alumina cements. Cem Concr Res 1992;22:1101–14.

[11] Majumdar AJ, Singh B, Edmonds RN. Hydration of mixtures of cement fondue aluminous cement and granulated blast furnace slag. Cem Concr Res 1990;20:197–208.

[12] Collepardi M, Monosi P, Piccioli P. The influence of pozzolanic materials on the mechanical stability of aluminous cement. Cem Concr Res 1995;25:961–8.

[13] Singh B, Majumdar AJ, Quillin K. Properties of BRECEM-10 year results. Cem Concr Res 1999;29:429–33.

[14] Quillin KC. Blended high alumina cements. Mater World 1993;1:103–5.

[15] Quillin KC, Majumdar AJ. Phase equilibria in the $CaO–Al_2O_3–SiO_2–H_2O$ system at 5 °C, 20 °C and 38 °C. Adv Cem Res 1994;6:47–56.

[16] Heikal M, Radwan MM, Morsy MS. Influence of curing temperature on the physico-mechanical characteristics of calcium aluminate cement with air-cooled slag or water-cooled slag. Ceramics-Silikáty 2004;48(4):185–96.

[17] Heikal M, Morsy MS, Radwan MM. Electrical conductivity and phase composition of calcium aluminate cement containing air-cooled and water-cooled slag at 20, 40, and 60 °C. Cem Concr Res 2005;35:1438–46.

[18] Scrivener KL. Historical and present day applications of calcium aluminate cements. In: Proceedings of the international conference on CAC, Edinburgh, UK; 2001. p. 3–23.

[19] EN 196-1. Methods of testing cement – Part 1: Determination of strength. Turkish Standard Institute; 2002.

[20] Neville A. High alumina cement concrete. New York: John Wiley and Sones Publications; 1975.

[21] Rashid S. Conversion of calcium aluminate cement hydrates conversion re-examined with synchrotron energy dispersive diffraction. J Mater Sci Lett 1994;13:1232–4.

[22] Collins RJ, Gutt W. Research on long-term properties of high alumina cement concrete. Mag Concr Res 1988;40:195–208.

[23] Teychenne DC. Long-term research into the characteristics of high alumina cement concrete. Mag Concr Res 1975;27:78–102.

[24] Alcocel EG, Garces P, Chinchon S. General study of alkaline hydrolysis in calcium aluminate cement mortars under a broad range of experimental conditions. Cem Concr Res 2000;30:1689–99.

[25] Building Research Establishment. Annual report. London; 1973. p. 15–6.

[26] Glasser FP, Zhang L, Zhou Q. Reactions of aluminate cement with calcium sulphate. In: Proceedings of the international conference on CAC, Edinburgh, UK; 2001. p. 551–64.