



Performance of belite–sulfoaluminate cements

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Abstract

Cements, which contain a high proportion of the mineral belite, often with an additional component such as calcium sulfoaluminate included to improve early strength development, are currently attracting a great deal of interest worldwide. This interest is largely due to their intrinsically lower energy requirements and CO₂ emissions on manufacture than conventional Portland cements (PC). The properties of two commercially produced belite–sulfoaluminate based cements have been studied. Concretes made using these cements show rapid strength development and excellent sulfate resistance. Compressive strength at 20°C is comparable with PC concretes made using similar cement contents and water-to-cement (w/c) ratios. However, carbonation rates under natural and accelerated conditions are high when compared with PC concretes made using similar mix designs. © 2001 Building Research Establishment. Published by Elsevier Science Ltd. All rights reserved.

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1. Introduction

The pressure to reduce energy consumption and CO₂ emissions during Portland cement (PC) manufacture has been one of the factors contributing to the development of novel cements with intrinsically lower energy requirements and CO₂ emissions on manufacture than conventional PC. Such cements are currently attracting a great deal of interest worldwide and a number of different types have been suggested and are at varying stages of development [1,2]. Of these, perhaps the greatest level of interest is being shown in cements that contain a high proportion of the mineral belite, C₂S¹ (an important component of PC), often with an additional reactive component such as calcium sulfoaluminate, C₄A₃S̄, included to improve strength development at early ages.

Belite-rich cements have several potential advantages over PC:

- The amount of energy theoretically required to manufacture belite-based cements is lower than that of PC. Alite (C₃S), the main component of PC, is formed at temperatures

of about 1450°C. Belite (C₂S) is formed at around 1200°C. Belite-based cements can therefore be manufactured at lower kiln temperatures than conventional PC. The total energy saving arising from the use of belite cements could be about 16% when compared with PC [3].

- The levels of CO₂ emitted during the manufacture of belite-based cements are lower than for PC. Total CO₂ emissions from cement manufacture could be reduced [4] by up to 10% through the use of belite cements. Reducing the burning temperature for cement clinker also reduces the emission of NO_x.

- The long-term strength and durability of concrete made from belite-based cements can potentially exceed those of PC.

- The manufacture of high belite-containing cements is also of materials conservation interest in some countries as it allows limestones with a lower carbonate content to be used.

Belite itself hydrates comparatively slowly [5,6] and early compressive strengths of pastes, mortars, and concretes containing belite cements are generally low as a result. The early strength can, however, be increased using a number of techniques. These include the mechanical activation of belite [7], the stabilisation of more reactive forms of belite [8,9], and the use of hydrothermal techniques to produce material with a very high surface area [10]. However, perhaps the most practical technique is the addition of a reactive compo-

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¹ Cement chemistry notation has been used: C=CaO, A=Al₂O₃, S=SiO₂, H=H₂O, S̄=SO₃, F=Fe₂O₃, c=CO₂.

nent such as calcium sulfoaluminate, $C_4A_3\bar{S}$ (in some cases together with $C\bar{S}$ and/or C_4AF). The hydration of this phase leads to the formation of ettringite ($C_6A\bar{S}_3H_{32}$) and so contributes to the early strength development [3]. $C_4A_3\bar{S}$ is formed at temperatures around 1100°C and so the energy consumed on manufacturing these cements should not be significantly greater than that of belite cement.

Belite cements will only have a significant impact in reducing energy consumption and CO₂ emissions if they are manufactured and used on a large scale. Ongoing process improvements are making PC manufacture more energy-efficient. The use of blended PC and improvements in the hydraulic activity of PC may also lead to significant energy savings by reducing the PC content of concrete. Such changes are likely, at least in the short term, to outweigh any potential benefits of belite cement use. It has, however, been suggested that belite sulfoaluminate cements would be good activators of additions such as ground granulated blast-furnace slag and pulverised fuel ash [11].

Although belite–sulfoaluminate cements have attracted a lot of interest, they have only been manufactured and used on a large scale in China. Current production exceeds 1 million tonnes (although this is only a small fraction of total cement manufacture in China) and these “Third Cement Series” materials have been used in a wide range of structural and nonstructural applications [12]. The clinker is manufactured by heating a mixture of limestone, bauxite (or red bauxite), and CaSO₄ at 1300–1350°C. The clinkering temperature is therefore 100–150°C lower than that for PC. This reportedly allows clinker output to be increased by more than 20% and coal consumption reduced by about 15% in comparison with PC. The cement clinkers are ground with other components such as gypsum. By varying the proportions of clinker, calcium sulfate, and additives, a number of different types of cement can be produced [12].

The hydration of belite–sulfoaluminate cements at ambient temperatures leads to the formation of ettringite as a major phase. It has been suggested that, due to the large amount of ettringite produced on hydration, concretes made using belite–sulfoaluminate cement may be particularly prone to carbonation. This process could lead either to deterioration in the concrete itself through changes in the solid volume of the cement paste, or to reinforcement corrosion through the loss of pH buffering capacity. Zhou and Glasser [13] have studied the effects of exposing synthetic ettringite to a moist CO₂-rich atmosphere. They found that the surfaces of ettringite pellets decomposed to a mixture of calcium carbonate, gypsum, hemihydrate, alumina gel, and water. A sulfate AFm phase was present in the interior of the pellets. Andac and Glasser [11] observed pH values (controlled by the presence of KOH) of 13.1 after 3 days, falling to 12.9 after 60 days in uncarbonated pastes made using similar cements. They also observed high chloride ion concentrations in the pore fluid that could also have implications for the protection of reinforcement in concretes made using these cements.

The concrete may also be susceptible to expansion and cracking through the delayed formation of ettringite [5] in situations where the concrete was subjected to elevated temperatures during curing, either due to external heating or to heat generated from the hydration process itself. Ettringite becomes increasingly soluble at elevated temperatures and, in PC at least, does not form at temperatures around 85°C and above. It will, however, reform on cooling and, if formed in significant amounts in hardened concrete, can lead to expansion and cracking. It is also possible that concretes made using belite–sulfoaluminate cements may be susceptible to deterioration at low temperatures through thaumasite ($C_3S\bar{S}cH_{15}$) formation [14] if exposed to a source of carbonate ions. The potential for thaumasite formation in these materials has not been assessed in the current programme.

This paper describes an experimental programme carried out at Building Research Establishment (BRE) to assess the performance of concrete made using commercially manufactured belite sulfoaluminate cements from China. A series of tests have been carried out in order to:

1. Determine the oxide and phase compositions of the anhydrous cements.
2. Assess the rate of strength development of concretes made using these cements on storage in water at 5°C, 20°C, and 38°C, and air at 20°C.
3. Determine the durability of concretes made using these cements with respect to strength retention, carbonation resistance, and sulfate resistance.
4. Determine their resistance to chloride ion ingress.
5. Determine the effects of temperature during curing on the subsequent dimensional stability of the concrete.

2. Experimental

Samples of two commercially produced cements have been obtained from the only known large-scale manufacturer of belite-based cements via the Chinese Building Materials Academy. These cements are a “rapid hardening” calcium sulfoaluminate cement (designated “SAC” in the following discussion) and a “rapid hardening” calcium ferroaluminate cement (designated “FAC”). The manufacturer classifies both cements in strength class #525. An analysis of the oxide compositions of the cements used in the study is given in Table 1.

2.1. Sample preparation and mix design

The testing programme is summarised in Table 2. Concrete specimens were prepared in accordance with BS1881: Part 125 [15] using Thames Valley gravel aggregates. The target mix design given in Table 3 was used in a small-scale trial to determine whether the concretes prepared using SAC

Table 1
Phase and oxide analyses of clinkers (wt.%)

Oxide	BRE studies	
	SAC	FAC
SiO ₂	11.16	3.05
TiO ₂	1.19	2.18
Al ₂ O ₃	24.41	31.39
Fe ₂ O ₃	2.29	4.96
CaO	40.92	40.19
MgO	2.89	0.74
K ₂ O	0.32	0.07
Na ₂ O	0.05	0.05
P ₂ O ₅	0.1	0.04
Cr ₂ O ₃	0.01	0.07
Mn ₃ O ₄	0.04	0.03
ZrO ₂	0.03	0.12
HfO ₂	<0.01	<0.01
PbO	<0.02	<0.02
ZnO	<0.01	<0.01
BaO	0.02	<0.01
SrO	0.1	0.11
SnO ₂	<0.01	<0.01
CuO	<0.01	<0.01
LOI	2.06	4.47
SO ₃ (after LOI and fusion)	14.66	12.17

and FAC remained workable for long enough to allow samples for the experimental programme to be prepared without the use of admixtures². The slumps of the mixes were measured at regular intervals to assess the change in workability over time as shown in Table 4. Data for a PC concrete made using the same mix design are included for comparison. Given the relatively short period of time between mixing and preparing test specimens (approximately 20–30 min), this mix design was considered to be suitable to allow the samples for the planned test programme to be prepared for both the SAC and FAC concretes. However, suitable retarders would be required for site concretes to ensure that adequate workability was retained during placement.

All specimens, other than those for heat curing, were cured in moist air for 24 h prior to demoulding. Concretes for storage at 5°C and 38°C were cured at these temperatures for 24 h prior to demoulding. Specimens used for assessing the sulfate and carbonation resistance of the concrete were stored in water at 20°C for an additional 2 days. Those for assessing sulfate resistance were then placed in sodium sulfate (1.5% SO₃) and magnesium sulfate (0.35% SO₃ and 1.5% SO₃) solutions at 20°C. The solutions were replaced at 90-day intervals. Specimens exposed to sulfate solutions were inspected visually after 90, 180, and 365 days. Compressive strengths were

measured after 365 days as discussed below. Specimens for assessing carbonation resistance were placed indoors (at 20°C and 65% RH) and in sheltered and unsheltered locations on the BRE exposure site at Garston. Specimens for marine exposure were placed in the tidal zone of the BRE exposure site at Shoeburyness in Essex.

Following casting, specimens for heat treatment were covered with a metal plate to retain moisture and placed in an oven at room temperature. The oven temperature was then slowly increased to 85°C over a period of 4 h and held at this temperature for 12 h. The oven was then left to cool to room temperature before the specimens were removed and demoulded. Additional control specimens were prepared. These were cured under damp hessian at 20°C prior to demoulding. All prism lengths were measured and the specimens stored in water at 20°C. Length measurements were then made at regular intervals as shown in Table 2.

Compressive strength determinations were carried out on 100-mm cubes in accordance with BS1881: Part 116 [16].

Carbonation depths were determined by spraying freshly fractured surfaces of concrete specimens with phenolphthalein indicator and measuring at five points along each edge of the specimen before averaging. Samples for accelerated carbonation studies were demoulded after 1 day and then cured in water to 3 days prior to storage in a nitrogen cabinet for up to 28 days. The samples were then exposed to a carbon dioxide-enriched atmosphere with a CO₂ level of 4.3% at 20°C and 65% RH. Carbonation depths were measured at regular intervals as described above.

Powder samples were taken by drilling from specimens exposed to marine conditions. Drillings, taken from all four long faces and combined to provide a representative sample, were collected to a depth of 31 mm in increments of 5 mm, the surface 1 mm being discarded. The samples were finely ground and pressed into discs for analysis by X-ray fluorescence for total chloride and calcium. The total cementitious content of the samples was calculated from the known CaO contents of the cement assuming the aggregate to be noncalcareous. The chloride contents were expressed as a percentage by mass of the cement content for each sample.

2.2. Phase analysis

The phase compositions of the cements were studied using thermogravimetric analysis (TGA) and X-ray diffraction (XRD). XRD was carried out by means of a Siemens D500 diffractometer using Cu K α radiation and operating at 40 kV and 30 mA. Data were accumulated over one scan of 2 θ between 5° and 50°. Assignments of lines were made by comparisons with JCPDS files. Calcite and gypsum were determined by TGA using a Du Pont 2000 instrument. About 20 mg of cement was heated from ambient temperature to 1000°C at a rate of 15°C/min. The

² The manufacturers recommend the use of specific water reducing and retarding admixtures with these concretes to allow suitable workability to be achieved with the use of a low w/c ratio. However, BRE was unable to obtain samples or information regarding the nature of these admixtures.

Table 2
Summary of testing programme on SAC and FAC concretes

Test	Specimen size	Details	Test ages (days)
Compressive strength	100-mm cubes (three replicate specimens)	water-stored at 20°C water-stored at 38°C water-stored at 5°C air-stored at 20°C	1, 3, 7, 28, 90, 180, 365, 730 28, 365 28, 365 1, 3, 7, 28, 90, 180, 365
Carbonation	200 × 75 × 75-mm prisms (two replicate specimens)	indoor external sheltered external unsheltered	90, 180, 365, 540, 730 90, 180, 365, 540, 730 90, 180, 365, 540, 730
Sulfate resistance	100-mm cubes (three replicate specimens)	Na ₂ SO ₄ (1.5% SO ₃) at 20°C MgSO ₄ (0.35% SO ₃) at 20°C MgSO ₄ (1.5% SO ₃) at 20°C	90, 365, 730 90, 365, 730 90, 365, 730
Accelerated carbonation	200 × 75 × 75-mm prisms (two replicate specimens)	see main text	7, 14, 28, 56
Expansion	200 × 75 × 75-mm prisms (two replicate specimens)	heat-cured at 85°C then stored in water at 20°C	1, 2, 3, 7, 14, 28, 56, 112, 180, 365
Chloride ingress	300 × 100 × 100-mm prisms	tidal zone at BRE marine exposure site at Shoeburyness	90

amounts of calcite and gypsum present were calculated from the respective weight losses between 650°C and 750°C (due to the loss of CO₂ from calcite) and at about 100–130°C (due to the loss of water from gypsum).

3. Results and discussion

3.1. Anhydrous phase composition

The phase compositions from XRD are given in Table 5. The weight losses and corresponding weight percent values for calcite and gypsum are given in Table 6.

The belite content of the FAC is, due to the low Si content, likely to be very low. This is confirmed by the XRD analysis in which C₂S was not unambiguously identified. However, Lan and Glasser [17] have shown that a notable feature of the clinker chemistry of these cements is the silica deficiency of the belite phase, which is likely to be compensated by substitution of Al and S in place of the Si on tetrahedral sites. The cement predominantly consists of the sulfate-containing phases C₄A₃S̄ and calcium sulfate.

The silica content and XRD analysis (from Tables 1 and 5, respectively) suggest that the SAC sample has a higher belite content than that of FAC but again the sulfate-containing phases are present in large amounts. Both cements have a very low alkali content suggesting that there would be a low risk of damage occurring through alkali silica reaction [18]. However, this has not been assessed in the current work.

3.2. Early age compressive strength development

Compressive strength development for SAC concrete is summarised in Table 7. That for FAC concrete is given in Table 8. Strength development for both SAC and FAC concretes stored in water at 20°C is shown as a percentage of 28-day strength in Fig. 1. Strength development in concrete prepared using other cements is also shown for comparison. These results show the following:

1. FAC concrete stored in water at 20°C initially gained in compressive strength at a faster rate than otherwise equivalent SAC concrete. However, the compressive

Table 3
Mix design used for SAC and FAC concrete

Cement #525	350 kg/m ³
Aggregate	
10–20 mm	802 kg/m ³
5–10 mm	401 kg/m ³
0–5 mm	648 kg/m ³ (35%)
Water (total) ^a	197 (w/c = 0.563)

^a Initially, a w/c ratio of 0.5 was planned. However, in order to achieve suitable workability, a small amount of extra water was added to the mixer for the SAC, increasing the w/c ratio to 0.563. The same mix design was then used for the FAC concrete.

Table 4
Workability against time for SAC, FAC, and PC concretes

Time (min)	Slump (mm)		
	SAC	FAC	PC
6	60	35	35
15	40	30	40
30	25	25	30
40	15	20	30
50	15	15	30
60	10	25	25
70	10	10	25
80	5	10	20
90	5	5	15

strength of SAC concrete continued to increase between 28 days and 2 years whereas that of FAC concrete levelled off. The ongoing strength development in SAC may be due to the hydration of the slow reacting belite component.

2. Direct comparisons between concretes made with different types of cement are difficult to make due to differences in mix design and curing conditions. However, the compressive strength of FAC concrete at 28 and 90 days is comparable [19] with that of C45 PC concrete with the same cement content of 350 kg/m^{-3} . The equivalent strengths for SAC concrete are slightly lower. Fig. 1, which shows compressive strength development as a percentage of the 28-day strength for water-stored SAC, FAC, PC, and calcium aluminate cement (CAC) concretes, suggests that strength development for SAC and FAC concrete is relatively faster than that of PC concretes up to 28 days. However, it is relatively slower than that of CAC concrete over this period.

3. The compressive strengths of SAC and FAC concretes that had been stored in air were initially higher than those of equivalent water cured concretes. However, at ages above 28 days, the water-stored SAC concrete had a higher compressive strength than equivalent air-stored concrete. The compressive strength of air-stored FAC concrete remained above that of equivalent water stored up to 2 years.

4. At 28 days, SAC concrete cured in water at 5°C or at 38°C showed similar strength development to that stored in water at 20°C . However, after 1 year, the compressive strength of SAC concrete stored in water at 38°C was significantly higher than that of equivalent concrete stored in water at 20°C or at 5°C . XRD analysis showed that the phases present at 28 days were similar to those present at 1 year. However, XRD peaks that were assigned to C_2ASH_8 were significantly higher after 1 year than at 28 days suggesting that hydration was still occurring.

5. In contrast, the compressive strengths at 28 and 360 days of FAC concrete cured in water at 5°C were significantly higher than those at 20°C . However, the compressive strengths of equivalent specimens stored in water at 38°C were slightly lower than those at 20°C .

6. The compressive strengths of SAC and FAC concretes that had been stored in sulfate solutions at 20°C for 2 years were comparable to those of equivalent cubes that had been

Table 6

Weight losses and weight percent (wt.%) of calcite and gypsum determined by TGA

	SAC (%)	FAC (%)
<i>Calcite</i>		
Weight loss	1.6	4.0
wt. %	3.6	9.1
<i>Gypsum</i>		
Weight loss	0.48	0
wt. %	2.1	0

stored in water at 20°C for the same period. There was no visual evidence of deterioration. XRD showed that the phase compositions of SAC specimens that had been stored in sulfate solutions were similar to those of equivalent specimens stored in water at 20°C .

7. XRD analyses show that ettringite was the main cement hydrate in all cases. However, there are some differences in the minor phases. C_2ASH_8 was present in specimens stored in water at 20°C and 38°C . CAH_{10} was present in the FAC concrete stored in water at 5°C .

3.3. Carbonation

Carbonation depths for SAC and FAC concretes are summarised in Tables 9 and 10, respectively, for indoor and outdoor (sheltered and exposed) samples.

The available data show that the rate of carbonation for FAC concrete is lower than that of the SAC concrete. Both types carbonated more readily than a comparable C45 PC concrete,³ which had a similar cement content and had been similarly treated.

XRD showed that the outer (carbonated) layer of SAC concrete stored indoors for 180 days contained significantly more calcite than did the uncarbonated centre. Ettringite was still detected in the carbonated layer, but was present in smaller amounts than in the centre. The ratios of the ettringite $15.78^{\circ} 2\theta$ to the calcite $29.41^{\circ} 2\theta$ peaks are given in Table 11.

Accelerated carbonation data are shown in Fig. 2 compared with data, taken from Ref. [19], for C45 PC and 50:50 PC/pfa concretes that were prepared and precured under similar conditions to those used for the SAC and FAC concretes. The cement content of the PC concrete was 350 kg/m^3 . The total water-to-cement (w/c) ratio was 0.54. The 50:50 PC/pfa concrete contained 226 kg/m^3 PC. The total w/c ratio (including pfa) was 0.36. These data show that SAC concrete tends to carbonate more rapidly than FAC concrete under accelerated conditions. This result is generally consistent with the results of normal carbonation given above.

Table 5

Phases present in SAC and FAC cements (from XRD)

Phase	SAC	FAC
C_2S	✓	?
C_3S		
C		
$\text{C}_4\text{A}_3\text{S}$	✓	✓
$\text{C}\bar{\text{S}}$	✓	✓
Cc	✓	✓
C_3A		
C_4AF	✓	✓
Gypsum	✓	

³ A C45 PC concrete that had been cured for 3 days and stored at 20°C and 65% RH showed carbonation depths of 2.7 mm after 90 days and 4.3 mm after 1 year [19].

Table 7
Compressive strength development in concrete prepared using SAC

Storage conditions	Compressive strength (MPa)								Phases detected by XRD after 365 days
	1 day	3 days	7 days	28 days	90 days	180 days	365 days	720 days	
Water-stored at 20°C	32.5	38.5	40.5	44.0	48.5	49.5	53.5	59	ettringite (s) C ₂ ASH ₈ (w), calcite (m)
Water-stored at 38°C	–	–	–	45.0	–	–	69.0	–	ettringite (s) C ₂ ASH ₈ (vw), calcite (s)
Water-stored at 50°C	–	–	–	42.0	–	–	54.0	–	ettringite (s), calcite (m)
Air-stored at 20°C	–	39.5	42.5	45.0	48.0	43.5	45.0	38.5	ettringite (m), C ₄ Ac _{0.5} H ₁₂ (m), calcite (s), aragonite(m)
Na ₂ SO ₄ 20°C (1.5% SO ₃)	–	–	–	–	–	–	57.5	63.5	ettringite (vs) C ₂ ASH ₈ (vw), calcite (w)
MgSO ₄ 20°C (0.35% SO ₃)	–	–	–	–	–	–	56.5	60.5	ettringite (vs) C ₂ ASH ₈ (vw), calcite (w)
MgSO ₄ 20°C (1.5% SO ₃)	–	–	–	–	–	–	54.0	57.5	ettringite (vs) C ₂ ASH ₈ (m), calcite (w)

XRD peaks: vs = very strong; s = strong; m = medium; w = weak.

Table 8
Compressive strength development in concrete prepared using FAC

Storage conditions	Compressive strength (MPa)								Phases detected by XRD after 365 days
	1 day	3 days	7 days	28 days	90 days	180 days	365 days	720 days	
Water-stored at 20°C	41.5	44.5	46.5	51.5	55.0	55.5	53.5	55.5	ettringite (s), C ₄ A ₃ \bar{S} calcite (s)
Water-stored at 38°C	–	–	–	46.5	–	–	48.0	–	ettringite (s), C ₂ ASH ₈ (vw) calcite (s)
Water-stored at 5°C	–	–	–	74.5	–	–	76.5	–	ettringite (s), CAH ₁₀ (m) calcite (m)
Air-stored at 20°C	–	48.0	51.5	55.5	55.5	57	53.5	53.0	ettringite (s), calcite (s)
Na ₂ SO ₄ 20°C (1.5% SO ₃)	–	–	–	–	–	–	51.5	55.5	
MgSO ₄ 20°C (0.35% SO ₃)	–	–	–	–	–	–	56.5	55.0	
MgSO ₄ 20°C (1.5% SO ₃)	–	–	–	–	–	–	56.5	55.5	

XRD peaks: vs = very strong; s = strong; m = medium; w = weak.

The data also show that, based on the limited data available, that both FAC and SAC carbonate more rapidly than a comparable PC concrete. They also carbonate faster than a

C45 50:50 PC/pfa concrete. However, the effects of curing regime and the effects of carbonation on the dimensional stability of the concrete have not been studied.

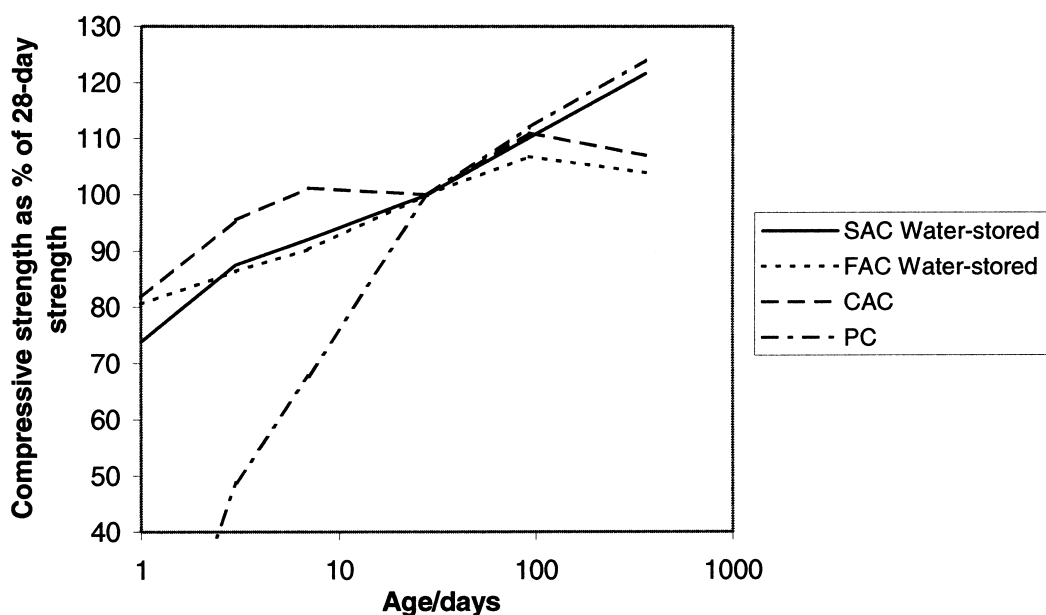


Fig. 1. Compressive strength development in SAC and FAC concrete at 20°C as a % of 28-day strength. Data for CAC and PC concretes are also shown for comparison.

Table 9
Mean carbonation depths for SAC concrete

Conditions	Mean carbonation depth (mm)				
	90 days	180 days	365 days	540 days	720 days
Indoor	5.0 (3–8)	6.1 (4–9)	11.6 (9–19)	11.1 (9–15)	14.5 (11–17)
Outdoor sheltered	2.0 (1–5)	4.3 (2–9)	6.2 (3.5–10.5)	7.2 (4.5–15)	8.7 (5–12)
Outdoor exposed	0	3.5 (1.5–8)	1.8 (1–6)	1.4 (0.5–3.5)	1.5 (1–4)

Note that values in brackets are the extremes of the range of measurements on three prisms.

Table 10
Mean carbonation depths for FAC concrete

Conditions	Mean carbonation depth (mm)				
	90 days	180 days	365 days	540 days	720 days
Indoor	3.1 (1–6)	4.6 (2.5–9)	7.0 (4–14)	6.9 (3.5–10)	10.5 (7–16)
Outdoor sheltered	2.6 (1–6.5)	3.4 (1–6.5)	4.6 (3–6.5)	6.2 (4–10)	8.0 (5.5–11)
Outdoor exposed	1.3 (1–2.5)	2.3 (1–7)	2.5 (1–6.5)	2.6 (1–5)	3.6 (1.5–7)

Note that values in brackets are the extremes of the range of measurements on three prisms.

3.4. Chloride ingress

The 90-day chloride profiles are summarised in Table 12. The data have been approximated to the diffusion equation:

$$C_x - C_b = (C_s - C_b) \left[1 - \operatorname{erf} \left(\frac{x}{2(Dt)^{1/2}} \right) \right]$$

Table 11
XRD peak heights for ettringite and calcite after 180 days in SAC concrete stored indoors

	Counts per second		E/C ratio
	Ettringite (E)	Calcite (C)	
Centre	316	121	2.61
Surface	151	437	0.35

where C_x is the chloride at depth x , C_s is the chloride content at surface of the concrete, C_b is the background chloride content, D is the effective chloride diffusion coefficient, and t is the exposure period.

The FAC concrete are consistent with a diffusion coefficient of $2.6 \times 10^{-11} \text{ m}^2/\text{s}$ and a surface chloride concentration of 0.8 wt.% of cement. The data for the SAC concrete could not be fitted to the curve. This diffusion coefficient is high, and the surface chloride concentration low when compared with those of PC concretes under similar conditions [19]. However, diffusion coefficients measured using this method have been found [20] to fall with time as a result of ageing and lower values may be recorded at later ages.

No significant changes in the length of heat-treated concrete prisms for either the SAC or the FAC concretes were observed over a period of 1 year. In studies of

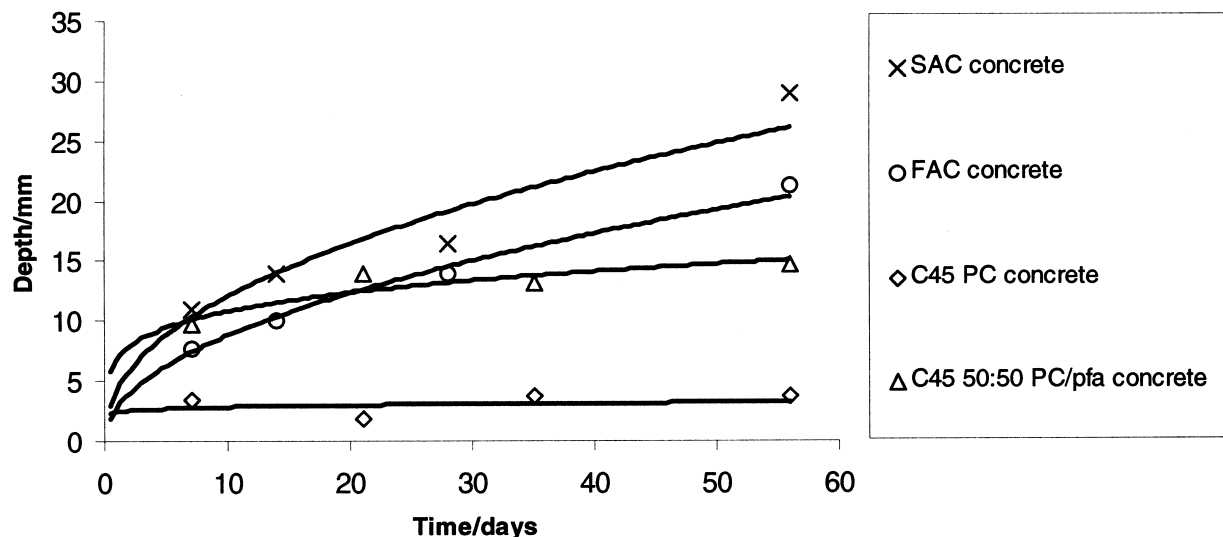


Fig. 2. Accelerated carbonation depths against time for SAC and FAC concrete. Concretes were cured for 3 days in all cases.

Table 12

Chloride content for powdered samples at specified depth intervals after 90 days

Depth (mm)	Chloride content (wt.% cement)	
	SAC	FAC
1–6	0.76	0.73
6–11	0.38	0.55
11–16	0.31	0.38
16–21	0.32	0.32
21–26	0.29	0.19
26–31	0.24	0.12
Background ^a	0.039	0.022

^a This was measured using equivalent concretes that had not been exposed to external chlorides.

expansion through delayed ettringite formation in PC concretes the expansion, where it occurred, had commenced within this timescale and continued over a period of about 1 year [21].

4. Conclusions

This report has described an experimental testing programme aimed at assessing the performance of concrete made using belite sulfoaluminate and belite ferroaluminate cements. The results obtained to date have shown the following:

1. Concretes prepared using SAC and FAC lose workability rapidly. For practical applications, a retarder would be required. The manufacturers recommend the use of specific water-reducing and retarding admixtures although these were not made available to BRE. However, there was sufficient time prior to setting to allow laboratory test samples to be prepared.

2. FAC concrete stored in water at 20°C initially gained in compressive strength at a faster rate than otherwise equivalent SAC concrete. However, the compressive strength of SAC concrete continued to increase up to 2 years whereas that of FAC concrete levelled off. The ongoing strength development in SAC may be due to the hydration of the slow reacting belite component. The compressive strength of FAC concrete at 90 days is similar to that of C45 PC concrete with the same cement content of 350 kg/m³.

3. Early strength development for SAC and FAC concrete is faster (relative to 28-day strength) than that of PC concretes. However, it is slower than that of CAC concrete.

4. Both SAC and FAC concretes have excellent sulfate resistance.

5. Based on the results of the current study SAC concrete carbonates more rapidly than equivalent FAC concrete. Both tend to carbonate more rapidly than PC concrete with a similar 28-day strength and equivalent cement content under similar curing and exposure conditions. Reinforcement in concretes made using these cements may therefore

be prone to corrosion as a result of the reduced pH of the pore solution. However, lower carbonation rates may have been observed if appropriate water-reducing admixtures had been available.

6. No significant changes in length of heat-treated prisms for either the SAC or the FAC concretes were observed over a 1-year period. Where expansion has occurred through delayed ettringite formation in PC concretes the expansion has generally been observed within 1 year under similar conditions.

7. The diffusion coefficient for FAC concrete was found to be high in comparison with PC concrete. Again, a lower value may have been observed if appropriate water-reducing admixtures had been available.

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References

- [1] C.D. Lawrence, The production of low-energy cements, in: P.C. Hewitt (Ed.), *Lea's Chemistry of Cement and Concrete*, fourth ed., Arnold, London, 1998, pp. 421–470.
- [2] J.H. Sharp, C.D. Lawrence, R. Yang, Calcium sulfoaluminate cements — low-energy cements, special cements or what? *Adv. Cem. Res.* 11 (1999) 3.
- [3] H. Uchikawa, Management strategy in cement technology for the next century: Part 3, *World Cem.*, (1994) 47 (November).
- [4] H. Uchikawa, Management strategy in cement technology for the next century: Part 2, *World Cem.*, (1994) 49 (October).
- [5] H.F.W. Taylor, *Cement Chemistry*, second ed., Thomas Telford, London, 1997.
- [6] W. Kurdowski, C. George, F. Sorrentino, Special cements, *Proc. 8th Int. Congr. Chem. Cem.*, Rio de Janeiro 1.
- [7] L. Jinyu, F. Yueming, Y. Jiazhi, The mechanical activation of belite, *Proc. 9th Int. Congr. Chem. Cem.* 3, NCB, New Delhi, 1992, p. 51.
- [8] J. Stark, A. Muller, R. Seydel, K. Jost, Conditions of the existence of hydraulically active belite cement, *Proc. 8th Int. Congr. Chem. Cem.*, Rio de Janeiro 2.
- [9] I. Mielke, A. Muller, J. Stark, Active belite cement, *Proc. 9th Int. Congr. Chem. Cem.*, New Delhi, India 2, NCB, New Delhi, 1992, p. 399.
- [10] H. Ishida, K. Mabuchi, K. Sasak, T. Mitsuda, Highly reactive β -C2S:1. Hydration behaviour at room temperature, *J. Am. Ceram. Soc.* 75 (1992) 353.
- [11] M. Andac, F.P. Glasser, Pore solution composition of calcium sulfoaluminate cement, *Adv. Cem. Res.* 11 (1999) 23.
- [12] L. Zhang, M. Su, Y. Wang, Development of the use of sulfo- and ferroaluminate cements in China, *Adv. Cem. Res.* 11 (1999) 15.
- [13] Q. Zhou, F.P. Glasser, Kinetics and mechanism of the carbonation of ettringite, *Adv. Cem. Res.* 12 (2000) 131.
- [14] The thaumasite form of sulfate attack: Risks, diagnosis, remedial works and guidance on new construction, Report of the Thaumasite Expert Group, UK Department of the Environment, Transport and the Regions, 1999.

- [15] BS1881: Part 125, Testing concrete: Methods for mixing and sampling fresh concrete in the laboratory, British Standards Institution, London, 1986.
- [16] BS 1881: Part 116, Method for determination of compressive strength of concrete cubes, British Standards Institution, London, 1983.
- [17] W. Lan, F.P. Glasser, Hydration of calcium sulfoaluminate cements, *Adv. Cem. Res.* 8 (1996) 127.
- [18] Alkali silica reaction in concrete, BRE Dig. 330.
- [19] M. Thomas, J.D. Matthews, Durability of pfa concrete, *Build. Res. Establ. Rep.* BR 216.
- [20] P. Bamforth, The derivation of input data for modelling chloride ingress from eight-year UK coastal exposure trials, *Mag. Concr. Res.* 51 (1999) 87.
- [21] K. Quillin, A. Barker, J. Matthews, unpublished experiments.