

ACCELERATED HARDENING OF MORTARS WITH HYDRAULIC BINDERS OF SILICA FUME/LIME



Harald Justnes,
 Dr. Ing., Senior Research Engineer,
 SINTEF Structures and Concrete,
 N-7034 Trondheim, NORWAY,
 Tel: +47-73 59 69 22, Fax: +47-73 59 71 36,
 E-mail: harald.justnes@kobe.sintef.no

Abstract

The compressive and flexural strengths of different silica fume/lime mortars were measured on 40-40-160 mm prisms after 1, 3 and 7 days curing under moist burlap at 20°C. The molar Ca/Si-ratio and the water/(CaO+SiO₂) ratio by mass were basically kept constant to 1.50 (ideal CSH-gel) and 0.75, respectively. 5 % superplasticizer was added to the mixing water in order to make castable mixes. Due to the slow pozzolanic reaction between lime and silica fume itself, different salts capable of forming alkali hydroxides *in situ* when they react with calcium hydroxide were added in order to achieve a high early strength. Both salt type (carbonates, fluorides, sulphates and phosphates) and dosage (0-15% of CaO+SiO₂) of some of the most effective salts (carbonates and phosphates) were varied. The early strengths increased with increasing dosage, but maximum strength at 7 days was reached with 5 % accelerator. Sodium salts gave higher strengths than their potassium analogues. An attempt of achieving high early strength by replacing CaO+SiO₂ with a rapid hardening portland cement (0-15%), gave no extra effect. The strength response to hot curing of the silica fume/lime mortars was increased when an accelerator was applied.

Key words: Silica fume, lime, pozzolanic reaction, accelerators

1. INTRODUCTION

Autoclaved mixes of lime and silica are well known as binders, but only a few studies have been made on the reaction between slaked lime and finely divided silica as rice husk ash (95 % S, $\approx 150 \text{ m}^2/\text{g}$) at ambient temperature; James and Rao /1/, Cook and Suwanvitaya /2,3/ and Cook /4/.

Justnes /5/ investigated the reaction between silica fume and lime with simulated pore water (KOH/NaOH = 2, and pH = 13) and tested the strength of mortars based on such binders. Justnes *et al* /6,7/ proposed a mechanism for the pozzolanic reaction of silica fume and lime where the alkalis from the cement had a catalytic effect. The silica fume/lime mortars with simulated pore water /5/ had a low early strength and the most obvious way to increase the early strength was to increase the OH⁻ concentration. However, since concentrated alkali hydroxides have very high pH and are considered hazardous liquids, it was decided to utilize solutions of salts with pH<12 and which would form hydroxides *in situ* in reaction with lime.

2. EXPERIMENTAL

2.1 Components

The condensed silica fume was a by-product from a ferrosilicon plant, containing 91.2 % SiO₂ (S) and with a specific surface of 22.6 m²/g as determined by N₂ adsorption (BET). The slaked lime, Ca(OH)₂ (CH), and burnt lime, CaO (C), was industrial grades being > 96 % pure.

The accelerators potassium carbonate, K₂CO₃, sodium carbonate, Na₂CO₃, potassium fluoride, KF, sodium fluoride, NaF, sodium sulphate, Na₂SO₄, and sodium phosphate dodeca hydrate, Na₃PO₄·12H₂O, were of the laboratory grade *purum* (>98%). An exception was the Na₃PO₄·12H₂O used for a serie with varying dosage, which was of the lower, unspecified "technical" quality.

The rapid hardening portland cement RP38, delivered by Norcem A/S, Brevik, Norway, was used as a partly powder replacement.

The sand was dry DIN 1164 Normensand from Beckum, Germany, supplied in bags of 1350±5 g.

2.2 Methods

2.2.1 Mixing and curing procedure

Two basic mixes were made; 1) 417 g S, 166 g C, 550 g CH and 586 g tap water and 2) 417 g S, 200 g C, 506 g CH and 597 g tap water. When all components have reacted, both compositions would give a molar ratio Ca/Si = 1.50 in the binder. Both mixes were added 50 g super-plasticizer dissolved in the tap water, while the accelerators were added as dry powders. This gives a water/dry powder-ratio (H/C+S) of 0.75 by mass for both mixes, which means that the water in both the super-plasticizer and the calcium hydroxide powder (i.e. chemical bound water) are taken into account. Thus, H/C+S is equivalent to the conventional w/c of a cement mix. To each mix, 2700 g sand was added to complete the mortar mixes having 1000 g of water free SiO₂ + CaO.

The powders and water were blended for about 1 min in a Hobart mixer of 5 l capacity. The mixes were very sticky and those with the highest accelerator dosages became rapidly earth moist. Thus, they had to be strongly vibrated or tamped into six 40·40·160 mm steel molds. The 6 prisms were demolded after 1 day and cured under moist burlap covered with plastic at 20°C. For some heat cured samples, the molds were put in plastic bags and lowered in water of 60°C for 3h.

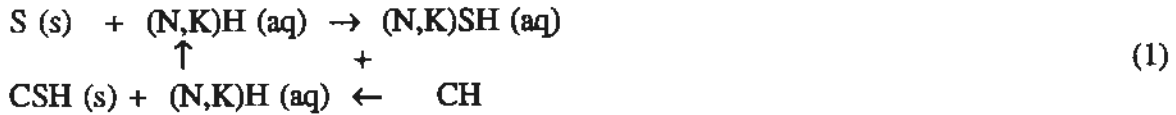
2.2.2 Flexural and compressive strength measurements

The flexural strength was measured on two prisms and the compressive strength on the 4 resulting end pieces after 1, 3, 7 (or 6) days curing. The test termins for the heat cured samples were 3 hours, 1 day and 3 days.

3. RESULTS AND DISCUSSION

3.1 Accelerator principle

Justnes *et al* proposed /6,7/ a mechanism for the pozzolanic reaction of silica fume in cement involving the alkalis of the cement as catalysts (i.e. not consumed in the process);



where C = CaO, S = SiO₂, N = Na₂O, K = K₂O, H = H₂O, (aq) = water-soluble and (s) = solid. This led to the use of partly simulated pore water (KH/NH = 2 to pH = 13) in another study /5/ of the reaction between silica fume and slaked lime, confirming a much more rapid reaction than found by Sellevold *et al* /8/ where alkalis were not included.

In order to avoid handling of aggressive alkali hydroxide solutions, a general concept was introduced where less alkaline salts reacted with calcium hydroxide and produced soluble alkali hydroxides and an insoluble calcium salt (by-product) *in situ*. The reaction can be generalised for an alkali salt (Na,K)_xA, where A = an anion forming calcium salts, Ca_xA₂, less soluble than calcium hydroxide (see Table 1);

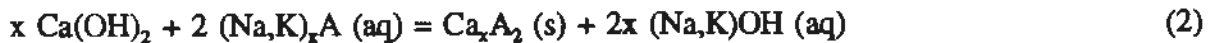


Table 1 The soluble product, K_{sp}, and equilibrium concentration of calcium, [Ca²⁺], for salts of general composition Ca_xA₂ (A=anion).

x	A	K _{sp}	[Ca ²⁺] (mM)
1	OH ⁻	5.5·10 ⁻⁶	11.1
1	F ⁻	5.3·10 ⁻⁹	1.1
2	CO ₃ ²⁻	2.8·10 ⁻⁹	.053
2	SO ₄ ²⁻	9.1·10 ⁻⁶	3.0
3	PO ₄ ³⁻	2.0·10 ⁻²⁹	.019

In general; the larger the difference in [Ca²⁺] for Ca(OH)₂ and Ca_xA₂, the more is reaction (2) shifted towards the right.

3.2 Factors determining early strength

3.2.1 Effect of accelerator type

The mass, flexural and compressive strengths for the prisms of lime/silica fume mortars accelerated with different type of salts are given in Table 2 after 1, 3 and 7 days curing. The compressive strength development for the same mixes are visualized in Figure 1.

Table 2 Mass, m (g), flexural strength, f_n (MPa), and compressive strength, f_c (MPa), of silica fume/lime mortars with different type of accelerators.

Basic mix	1	2	2	2	2	2	2	2
Accelerator	None	6.5 % $2K_2CO_3/Na_2CO_3$	7.0 % K_2CO_3	6.0 % Na_2CO_3	5.89 % KF	4.75 % NaF	8.04 % Na_2SO_4	14.34 % $Na_3PO_4 \cdot 12H_2O$
<u>1 day</u>								
m (g)	534±1	524±3	535±5	528±1	527±1	535±0	531±3	533±2
f_n (MPa)	.07±.00	2.0±.3	2.2±.1	1.9±.1	1.42±.02	2.5±.2	.21±.07	2.35±.08
f_c (MPa)	.28±.00	4.9±.1	5.1±.1	5.6±.1	3.3±.4	5.78±.04	.50±.02	6.6±.2
<u>3 days</u>								
m (g)	534±3	525±2	538±4	538±2	529±4	531±0	531±2	531±4
f_n (MPa)	.30±.00	3.7±.4	4.0±.3	4.1±.3	3.7±.1	3.4±.4	.89±.03	4.0±.3
f_c (MPa)	1.0±.1	10.3±.2	9.8±.1	11.2±.5	9.1±.5	12.3±.7	3.2±.1	13.4±.3
<u>6 days</u>								
m (g)	532±1 ¹	527±2 ¹	536±2	530±2	534±1	526±4	530±2	532±0
f_n (MPa)	1.26±.07 ¹	4.9±.3 ¹	4.0±.1	4.5±1.2	4.0±.2	2.7±.7	3.07±.03	4.3±.3
f_c (MPa)	5.60±.06 ¹	18.0±.5 ¹	15.4±.5	18.2±.4	16.1±.5	18.1±.8	9.6±.2	18.6±.6

¹Values after 7 days curing.

The 2:1 mix of potassium:sodium carbonate originates from the 2:1 mix of potassium:sodium hydroxide in the former study /5/. However, then /5/ the concentration of hydroxyl ions, $[\text{OH}^-]$, was 10^{-1} M, corresponding to $\text{pH} = 13$. In the present study 65 g of the $2\text{K}_2\text{CO}_3 + \text{Na}_2\text{CO}_3$ blend correspond to about 0.5 mole of carbonate generating 1 mole of hydroxide in reaction with calcium hydroxide according to equation (2). The $[\text{OH}^-]$ in the initial water phase will be $1 \text{ mole} / (597 + 30) \text{ ml} = 1.67 \text{ M}$, corresponding to a pH of 14.2 or 16 times the concentration applied earlier /5/.

The masses of the single accelerators in Table 2 is adjusted in such a way that all sodium salts should generate 1.13 mole NaOH and all potassium salts should generate 1.01 mole KOH according to equation (2). The maximum pH of the water immediately after mixing will then be 14.2 (as for the blend), assuming that reaction (2) is complete.

According to the results in Table 2 and Figure 1, sodium sulphate is the least effective accelerator, which is natural according to the principle described in section 3.1 and the data in Table 1 (i.e. equilibrium concentration of Ca^{2+} over gypsum only 3.5x lower than over calcium hydroxide, while for instance it is 10x lower over calcium fluoride).

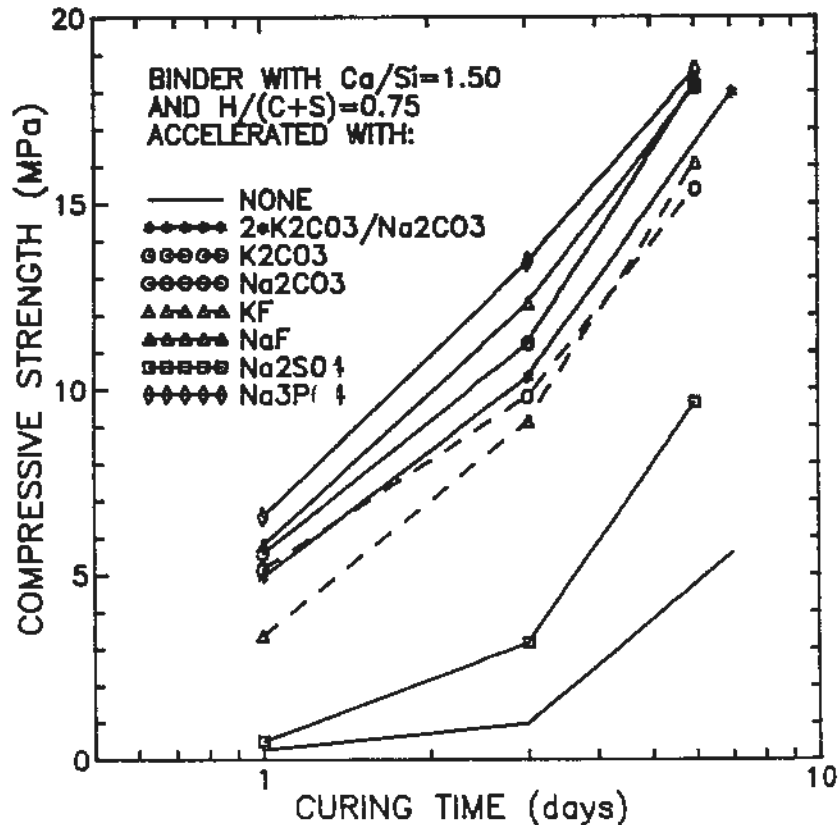


Figure 1 The compressive strength evolution for silica fume/lime mortars with different types of accelerators at equimolar dosages

Furthermore, the sodium salts are more effective accelerators than their potassium analogues, at least with respect to the strength development. This may be due to several reasons: 1) The solubility of sodium silicates are higher than potassium silicates (reaction intermediates in equation (1)). Perhaps the maximum concentration of potassium silicate is reached, which may give a lower cycle rate in equation (1) than for the sodium (not saturated) analogues. 2) Some of the potassium may be chemically bound in the CSH-gel and removed from the cycle in equation (1) or create a weaker CSH-gel by its incorporation.

The accelerator efficiency was $\text{Na}_3\text{PO}_4 \cdot 12\text{H}_2\text{O} > \text{NaF} > \text{Na}_2\text{CO}_3 > \text{K}_2\text{CO}_3 > 2 \text{K}_2\text{CO}_3 + \text{Na}_2\text{CO}_3 > \text{KF} > \text{Na}_2\text{SO}_4$ with respect to the 1 day and 3 days compressive strength. One day strengths exceeding 20 times the reference without accelerator was achieved.

3.2.2 Effect of accelerator dosage

The optimum accelerator dosage was determined by varying the dosage of the two accelerators $2\text{-K}_2\text{CO}_3 + \text{Na}_2\text{CO}_3$ and Na_3PO_4 from 0-15 % of the dry $\text{CaO} + \text{SiO}_2$, which is analogous to % by weight of cement. The mass, flexural and compressive strengths for the prisms of lime/silica fume mortars accelerated with the carbonate blend and the sodium phosphate accelerators are listed in Table 3 and 4, respectively, while their compressive strengths as a function of accelerator dosage are depicted in Figures 2 and 3, respectively.

The carbonate blend accelerator achieved maximum 1 day strength for a 10 % dosage, but only marginally better than a 5 % dosage, while the maximum 3 and 7 days strengths were obtained for the 5 % dosage (i.e. higher dosages lead to lower strengths).

The compressive strength profiles for the phosphate accelerator revealed no distinct optimum accelerator dosage. The 1 day and 3 days strengths increased steadily with the phosphate dosage, while the 7 days compressive strength was not significantly altered when the dosage exceeded 5 %. The 7 day flexural strength, on the other hand, was significantly higher for the highest phosphate dosage.

In a study /9/ of the system calcium-phosphate-silicate for chemical bound ceramics, it was concluded that hydroxy-apatite, $\text{Ca}_5(\text{PO}_4)_3\text{OH}$, was formed rather than calcium phosphate, $\text{Ca}_3(\text{PO}_4)_2$, and that phosphate may be included in a C-S-P-H gel. The difference between the carbonate and phosphate accelerator may thus be that hydroxy-apatite unlike calcium carbonate may possess a binding capacity by itself or by bridging CSH-gel.

3.2.3 Effect of binder replacement with cement

An attempt of achieving high early strength by replacing $\text{CaO} + \text{SiO}_2$ with a rapid hardening portland cement was made. The mass, flexural and compressive strengths for the prisms of lime/silica fume mortars with 0-15 % cement replacement are given in Table 5 and their compressive strengths as a function of cement replacement is plotted in Figure 4. Evidently, the cement replacement gave no significant change in strength at any age (exception for 10 % cement at 1 day). The reason for this may be retardation of the cement by the high SP dosage or carbonate ions.

Table 3 Mass, m (g), flexural strength, f_n (MPa), and compressive strength, f_c (MPa), of silica fume/lime mortars as a function of dosages of a carbonate blend.

Base mix/ Dose (%)	1/ 0.0	1/ 1.0	1/ 2.5	2/ 5.0	2/ 6.5	2/10.0	2/15.0
<u>1 day</u>							
m (g)	534±1	545±0	530±3	532±3	524±3	538±1	542±1
f_n (MPa)	.07±.00	.15±.02	.42±.00	1.84±.08	2.0±.3	2.00±.05	1.1±.1
f_c (MPa)	.28±.00	.52±.02	1.50±.04	4.5±.1	4.9±.1	5.17±.09	3.8±.1
<u>3 days</u>							
m (g)	534±3	541±1	532±2	534±3	525±2	528±6	542±2
f_n (MPa)	.30±.00	.43±.08	1.95±.05	3.8±.2	3.7±.4	3.60±.07	0.8±.0
f_c (MPa)	1.0±.1	2.9±.2	7.4±.3	10.5±.2	10.3±.2	9.94±.09	6.3±.3
<u>7 days</u>							
m (g)	532±1	538±2	531±1	536±1	527±2	529±4	537±1
f_n (MPa)	1.3±.1	1.6±.3	4.0±.1	3.6±.5	4.9±.3	4.9±.2	3.4±.1
f_c (MPa)	5.6±.1	9.0±.4	15.3±.2	18.1±.7	18.0±.5	16.2±.5	14.1±.8

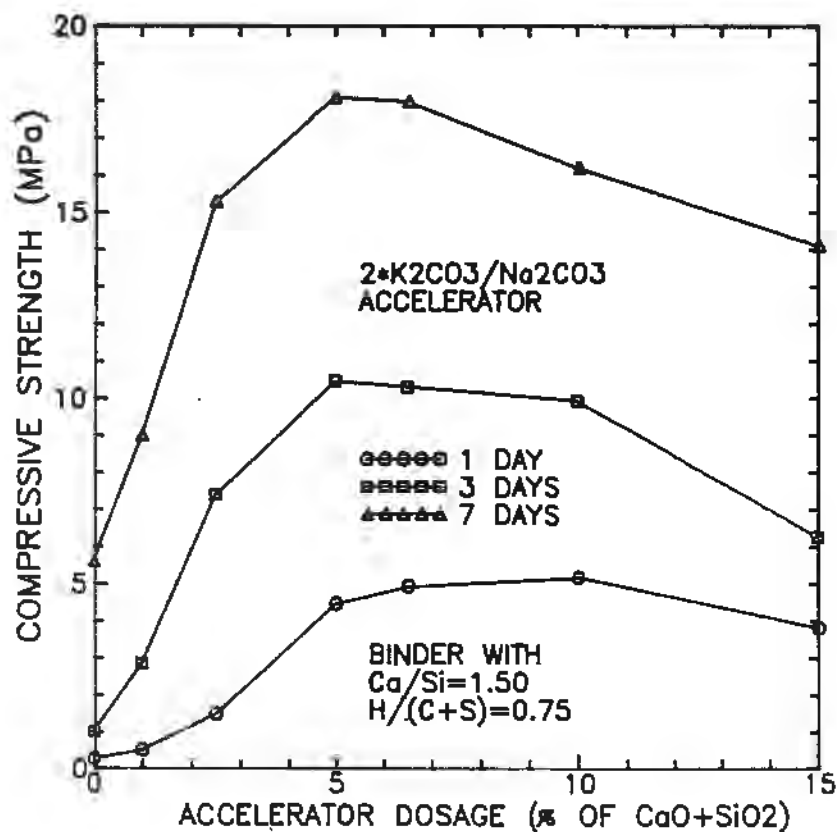


Figure 2

The compressive strength at 1, 3 and 7 days for silica fume/lime mortars as a function of dosage of a carbonate blend accelerator.

Table 4 Mass, m (g), flexural strength, f_f (MPa), and compressive strength, f_c (MPa), of silica fume/lime mortars as a function of technical sodium phosphate dosage.

Base mix/ Dose (%)	1/ 0.0	2/ 2.5	2/ 5.0	2/10.0	2/15.0
<u>1 day</u>					
m (g)	534 \pm 1	527 \pm 1	514 \pm 7	536 \pm 1	540 \pm 2
f_f (MPa)	.07 \pm .00	.15 \pm .08	.56 \pm .10	1.73 \pm .07	2.2 \pm 1
f_c (MPa)	.28 \pm .00	.47 \pm .11	1.19 \pm .09	3.6 \pm .3	5.3 \pm .2
<u>3 days</u>					
m (g)	534 \pm 3	529 \pm 1	520 \pm 2	525 \pm 3	540 \pm 2
f_f (MPa)	.30 \pm .00	.95 \pm .12	2.8 \pm .2	3.2 \pm .1	3.7 \pm .2
f_c (MPa)	1.0 \pm 1	2.8 \pm .2	6.6 \pm .3	7.9 \pm .4	9.6 \pm .8
<u>7 days</u>					
m (g)	532 \pm 1	531 \pm 1	519 \pm 1	536 \pm 1	549 \pm 2
f_f (MPa)	1.3 \pm .1	4.04 \pm .08	3.79 \pm .07	3.7 \pm .2	4.7 \pm .2
f_c (MPa)	5.6 \pm .1	11.4 \pm 1.1	14.2 \pm .7	13.6 \pm .4	14.9 \pm .2

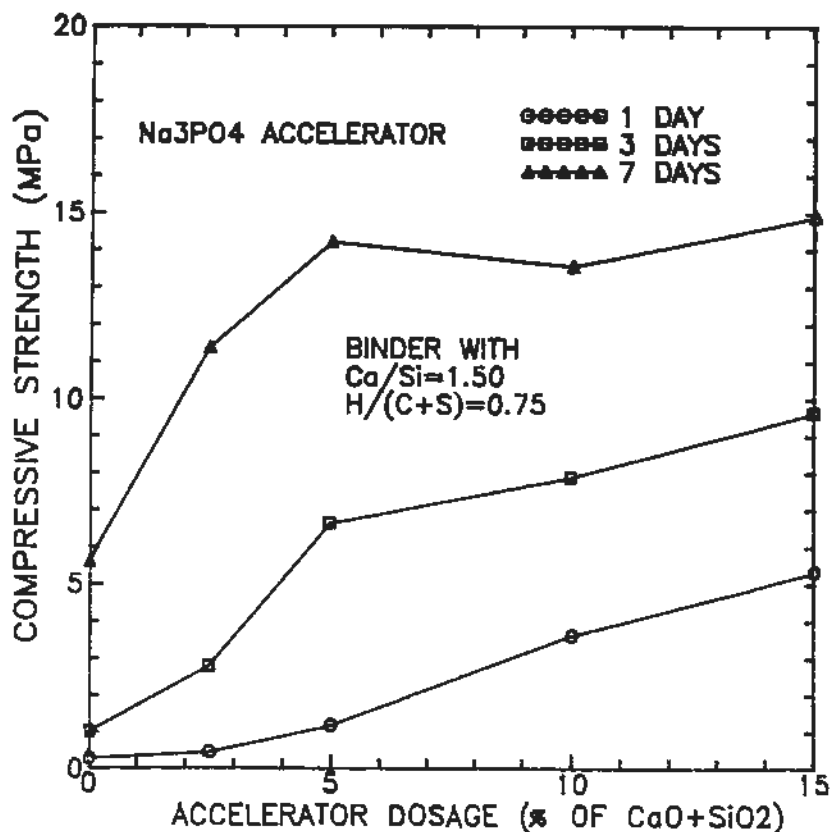


Figure 3 The compressive strength at 1, 3 and 7 days for silica fume/lime mortars as a function of dosage of sodium phosphate accelerator.

Table 5 Mass, m (g), flexural strength, f_n (MPa), and compressive strength, f_c (MPa), of silica fume/lime mortars as a function of replacement of $\text{CaO}+\text{SiO}_2$ with rapid hardening portland cement.

Replacement (%)	0.0	5.0	10.0	15.0
<u>1 day</u>				
m (g)	532 \pm 3	534 \pm 8	525 \pm 1	537 \pm 2
f_n (MPa)	1.84 \pm .08	1.6 \pm .2	1.3 \pm .3	1.3 \pm .1
f_c (MPa)	4.5 \pm .1	4.2 \pm .2	8.2 \pm .2	4.2 \pm .2
<u>3 days</u>				
m (g)	534 \pm 3	536 \pm 2	529 \pm 3	535 \pm 5
f_n (MPa)	3.8 \pm .2	3.0 \pm .4	3.28 \pm .03	3.03 \pm .08
f_c (MPa)	10.5 \pm .2	9.6 \pm .5	10.5 \pm .6	9.5 \pm .5
<u>7 days</u>				
m (g)	536 \pm 1	527 \pm 3	535 \pm 1	533 \pm 4
f_n (MPa)	3.6 \pm .5	3.7 \pm .1	4.9 \pm .5	5.0 \pm .5
f_c (MPa)	18.1 \pm .7	15.7 \pm 1.9	17.9 \pm .8	16.5 \pm .5

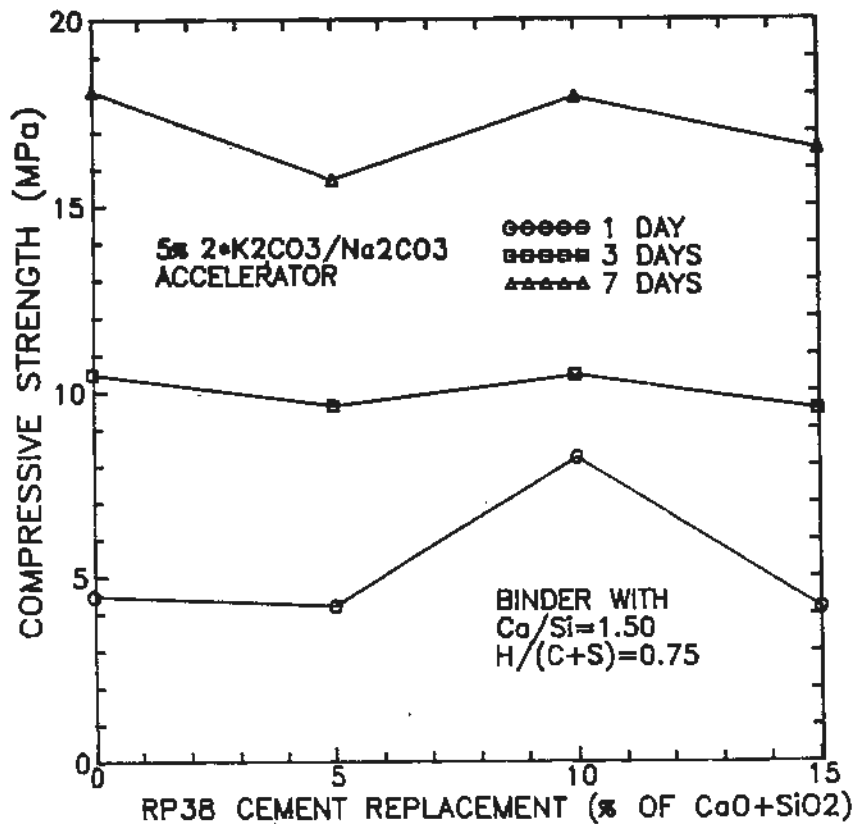


Figure 4 The compressive strength at 1, 3 and 7 days for silica fume/lime mortars as a function of replacement of $\text{CaO}+\text{SiO}_2$ with rapid hardening portland cement.

3.2.4 Effect of the initial curing temperature

The temperature response of lime/silica mortars was investigated by heat curing prisms at 60°C for 3 h, followed by 20°C curing. The mass, flexural and compressive strengths for the prisms of lime/silica fume mortars with 0.0 and 6.5 %, and cured according to this scheme, are listed in Table 6.

Table 6 The effect of initial hot curing on mass, m (g), flexural strength, f_n (MPa), and compressive strength, f_c (MPa), of silica fume/lime mortars with 0.0 and 6.5 % carbonate blend accelerator.

Base mix/ Dose (%)	1/ 0.0	2/ 0.0	2/ 6.5	2/6.5
<u>3 h at 60°C</u>				
m (g)	-	524±2	-	516±3
f_n (MPa)	-	.56±.10	-	3.4±.3
f_c (MPa)	-	1.40±.04	-	16.9±1.5
<u>1 day</u>				
m (g)	534±1	529±2	524±3	520±5
f_n (MPa)	.07±.00	.47±.07	2.0±.3	3.1±.4
f_c (MPa)	.28±.00	1.28±.16	4.9±.1	16.0±2.0
<u>3 days</u>				
m (g)	534±3	530±1	525±2	515±10
f_n (MPa)	.30±.00	1.29±.07	3.7±.4	2.8±.1
f_c (MPa)	1.0±.1	3.8±.1	10.3±.2	15.9±2.9
<u>7 days</u>				
m (g)	532±1	-	527±2	-
f_n (MPa)	1.3±.1	-	4.9±.3	-
f_c (MPa)	5.6±.1	-	18.0±.5	-

The heat response of lime/silica mortars without accelerator is moderate according to Table 6, with a compressive strength at 3 h slightly higher than the 3 days strength of the same mortar cured at 20°C only. Since the solubility of calcium hydroxide is lower at 60°C (1.21 g/l) than at 20°C (1.73 g/l), it is assumed that the acceleration is due to increased solubility of silicate (including traces of sodium salts) forming precipitates at the surface of CH (see Eq. 1). The heat response when 6.5 % carbonate blend accelerator is included, on the other hand, is dramatic with a 3 h strength close to the 7 days strength of an analogous mortar cured at 20°C only. However, the flexural strength is significantly reduced. If CSH gel is formed on the surface of CH, the heat cure may lead to an encapsulation of CH grains by a dense CSH and weaker zones in between and/or an overall CSH gel with lower C/S-ratio. In an earlier work /5/ it was found that the optimum C/S-ratio for flexural strength after 7 days curing was 1.11 and that the flexural strength decreased with decreasing C/S, while the 7 days compressive strength increased with decreasing C/S.

3.2.5 Effect of the molar Ca/Si ratio

A mix was made where the content of S, C and CH was changed to 600, 137 and 347 g, respectively, resulting in a molar Ca/Si = 0.71 and a H/C+S = 0.71. The mix was accelerated by 6.5 % of the carbonate blend accelerator. After 1, 3 and 7 days curing of the lime/silica mortar prisms, their masses were 523 ± 7 , 516 ± 12 and 471 ± 22 g, their flexural strengths were 1.8 ± 2 (-7.7%), 3.4 ± 1.2 (-8.8%) and 3.11 ± 0.07 MPa (-36.4%), and their compressive strengths were 5.9 ± 6 (+19.7%), 10.3 ± 1.3 ($\pm 0\%$) and 13.2 ± 1.8 MPa (-26.7%), respectively. The percentages in brackets after the strengths are the relative changes compared with a similar mortar with Ca/Si = 1.50 and H/C+S = 0.75.

The tendency of increasing early strength and decreasing later strength with decreasing C/S-ratio confirm the observations in the more thorough study on this topic /5/.

Note that when reaction (2) occur, some of the calcium is made unavailable for the pozzolanic reaction, and the potential Ca/Si ratio for the binder is lowered. For the 6.5 % carbonate blend resulting in 0.5 mole carbonate, the Ca/Si ratio is lowered from 1.50 to 1.42, and from 1.50 to 1.33 when 15 % of this accelerator is applied.

4. CONCLUSIONS

The strength development of mortars with lime/silica binders can be accelerated by adding salts that will form alkali hydroxides *in situ* in reaction with lime.

Examples of such salts are alkali carbonates, fluorides, phosphates and sulphates. Among these, carbonate or phosphate are the most effective and sulphates the least effective.

Sodium salts gave higher strengths than their potassium analogues.

The early strengths increased with increasing carbonate or phosphate dosage, but maximum strength at 7 days was reached with 5 % accelerator.

An attempt of achieving high early strength by replacing CaO+SiO₂ with a rapid hardening portland cement gave no extra effect.

The strength response to hot curing of the silica fume/lime mortars was increased when a carbonate accelerator was applied.

5. REFERENCES

- /1/ James, J. and Rao, M. S.; "Reaction Product of Lime and Silica from Rice Husk Ash", *Cement and Concrete Research*, 1986, 16, pp. 67-73
- /2/ Cook, D. J. and Suwanvitaya, P., Proc. 1st International Conference of Fly Ash, Silica Fume and other Mineral-by-Products in Concrete, Montebello, 1983 (ACI SP-79), 2, p. 831
- /3/ Cook, D. J. and Suwanvitaya, P., Proc. ESCAP/RCTT Third Workshop on Rice-Husk Ash Cement, New Dehli, India, 1981.
- /4/ Cook, D. J., Proc. 9th Australian Conference on the Mechanics of Structures and Materials, Sydney, Australia, 1984, p. 335.
- /5/ Justnes, H.; "Hydraulic binders based on condensed silica fume and slaked lime", The 9th International Congress on the Chemistry of Cement, New Dehli, India, 23-28 November, 1992, Vol. III, pp. 284-290.
- /6/ Justnes, H., Sellevold, E.J. and Lundevall, G.; "High Strength Concrete Binders. Part A: Reactivity and Composition of Cement Pastes with and without Condensed Silica Fume." 4th International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Istanbul, May 3-8, 1992, CANMET/ACI SP 132-47 (Vol. 2) pp. 873-889.
- /7/ Justnes, H., Meland, L, Bjørgum, J.O. and Krane, J.: "The Mechanism of Silica Fume Action in Concrete Studied by Solid State ^{29}Si MAS NMR", In "Applications of NMR to Cement Science", Editors: P. Colombet and A.R. Grimmer, A Gordon and Breach book, ISBN: 2-88124-965-5, April 1994, pp. 213-228.
- /8/ Sellevold, E.J., Bager, D.H., Klitgaard Jensen, E. and Knudsen, T.: "Silica Fume - Cement Pastes: Hydration and Pores Structure", Proceedings of the Nordic Research Seminar "Condensed Silica Fume in Concrete", 10th December 1981, Report BML 82.610, NTH, 1982-02-15, pp. 19-50.
- /9/ Hu, J., Agrawal, D.K. and Roy, R.: "Studies of Strength Mechanisms in Newly Developed Chemically Bonded Ceramics in the System $\text{CaO-SiO}_2\text{-P}_2\text{O}_5\text{-H}_2\text{O}$ ", *Cement and Concrete Research*, Vol. 18, 1988, pp. 103-108.