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Strength development of lime–pozzolana pastes with silica fume and fly ash



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HIGHLIGHTS

- Lime–pozzolana pastes (LPP) with ordinary strength has been produced.
- Inclusion of silica fume is necessary for LPP to gain high early strength.
- Water curing at 60 °C improves the 28-day strength of the LPP by 40%.
- Strength loss occurs in water-cured specimens during hydration time of 28–90 days.
- Carbonated outer shell in air-cured specimens reduces strength gain.

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ABSTRACT

This study explores the lime–pozzolana pastes made from high calcium hydrated lime blended with type F fly ash and silica fume, with the total pozzolana content up to 40%. Research focuses on the development of the compressive strength by varying the water–binder ratio, powder proportioning, fineness of lime, and curing conditions. The lime–pozzolana cement shows good promise as a binder which can be used alongside the Portland cement. With lower unit weight and higher compressive strength per unit weight than the Portland cement paste, the lime–pozzolana pastes can reduce the weight of structural elements and the overall cost of structures.

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1. Introduction

High energy and raw material consumption and high CO₂ emission during the production of the Portland cement (PC) have raised concerns over the sustainability of concrete use. Mitigation methods adopted include blending PC with pozzolana, which reacts with lime produced by the hydration of PC, to produce more cementing materials. Many pozzolanas such as fly ash (FA) and silica fume (SF) are industrial waste products which do not need further processing and their use in cement reduces the consumption of energy and raw materials and the emission of CO₂. Natural lime can be blended with larger amounts of pozzolana and can also gain strength by the carbonation of free lime, thereby reducing the CO₂ profile of the cement. Calcination temperatures for the limes are lower than that for producing PC clinker so the energy for cement

production is reduced. Lime–pozzolana cement (LPC) is greener than PC. The lighter unit weight of lime–pozzolana pastes (LPPs) compared to Portland cement paste (PCP) reduces the dead weight of structural elements and can reduce the building costs.

Archeological excavations have shown that lime is among the earliest binders used by man. Theoridou et al. [1] found that in Cyprus, lime mixed with crushed bricks was used as early as in 1200 B.C. Hydraulic lime was used widely by Romans, who added volcanic ash or finely ground burnt clay tiles, and later added sand and crushed stone or bricks to the paste to make the first lime–pozzolana concrete in history [2]. Lime was also used by early builders in central America [3] and in China during and after the Ming dynasty [4].

Recent publications by Grist et al. [5], Day and Shi [6], and Lanas et al. [7] show revived interest in lime-based binders. Grist et al. blended natural hydraulic lime with 25% SF and 25% FA by mass, prepared mortar specimens in accordance with BS EN-196-1, and then cured the specimens in water for up to 90 days. The strength rose continuously to cubic crushing strengths of 19.9 MPa at

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Table 1
Typical chemical compositions and burning temperatures of lime and cement.

Material	Chemical compositions (%)					Burning temperature (°C)
	CaO	MgO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	
NHL	96.0	1.0	1.5	0–1.5	0–1.5	900–950
HL	54.3	7.7	12.6	5.4	1.2	1000–1250
PC	60–67	0.5–4	17–25	3–8	0.5–6	1250–1450

28 days and 29.8 MPa at 90 days. The authors also made mortar specimens with lime blended with 30% SF and obtained 28-day and 90-day strengths of 28.7 MPa and 37.6 MPa, respectively. Day and Shi [6] tested paste specimens made by hydrated lime with natural pozzolana of 554 m²/kg Blaine fineness in a mass ratio of 1:4 and incorporated calcium chloride as reaction activator. Specimens were cured in water at 50 °C for up to 90 days. The authors obtained 28-day and 90-day cylindrical crushing strengths of 17 MPa and 19 MPa, respectively. Strength rose continuously until 14 days, remained constant until 28 days, and then rose slightly until 90 days. Lanás, et al. [7] tested mortar specimens made with natural hydraulic lime and sand in a ratio of 1:1 by volume and cured in water at ambient laboratory conditions until 365 days. The 28-day and 365-day cubic crushing strengths were 9 MPa and 16 MPa, respectively. Between the hydration times of 28 and 180 days, the strength increased only slightly to 9.5 MPa but rose steadily after 180 days. In summary, specimens in most of the studies were cured in water until the time of testing and had high strengths. However, onsite structures are often cured in water for only limited periods. In view of this issue, this study investigates the strength development of the paste when exposed to air after an initial water curing regime.

Calcitic or high calcium hydrated lime is obtained by burning calcite (CaCO₃) bearing rocks, such as limestone and chalk, at 900–1250 °C to release CO₂ and produce quick lime (CaO). Water is added to the lime to produce hydrated lime (Ca(OH)₂). The calcite bearing sands and shells of eggs, snails, oysters and sea organisms can also be used in lime production. Hydraulic lime (HL) contains significant natural quantities of silica and alumina and sets in both air and water. Non-hydraulic lime (NHL) sets only in moist air but also sets in water when mixed with pozzolana. Table 1 shows the typical chemical compositions and burning temperatures of NHL [8], HL [7], and PC [2,8]. The choice of NHL over HL is preferred due to the lower calcination temperature range of NHL and the reduced production energy. In addition, NHL has 40% more CaO than HL. Therefore, when NHL blends with more pozzolana, the production energy, raw materials and CO₂ emission is further reduced. Pozzolanas contain reactive silica and alumina. Among the pozzolans, FA is a by-product of burning coal and rich in reactive silica and alumina. Type F FA has a low amount of CaO compared to type C FA. SF is a powder with particles finer than cement, consisting almost entirely of very reactive silica. It is a by-product during the manufacture of silicon and ferro-silicon alloys.

Lime–pozzolana paste (LPP) hardens partly by the chemical reaction of calcium hydroxide in hydrated lime with silica and alumina in pozzolana in the presence of water to form cementing C–S–H and C–A–H phases as shown in Eq. (1) and (2).

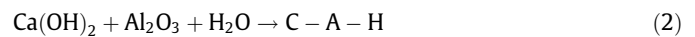
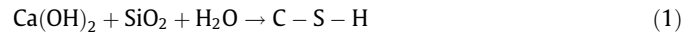
Table 2
Chemical and physical properties of raw materials.

Raw materials	Chemical compositions (%)							Specific gravity
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Ca(OH) ₂	CaCO ₃	MgO	
NHL	1.5	1.0	0.5	–	90.0	6.0	1.0	2.45
FA	58.3	27.9	3.3	4.4	–	–	–	2.00
SF	93	2.0	1.0	1.2	–	–	0.5	2.31
PC	20.4	4.4	3.3	63.2	–	2.0	3.2	3.11

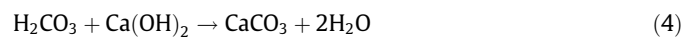
Table 3
Mixing proportions and curing conditions of specimens used to explore variations in pozzolana content and w/b.

Pozzolana Content (%)	Paste composition by weight (%)			Curing conditions		
	SF	FA	NHL	0–7 days	7–14 days	14–28 days
10	10	00	90	Mold	Air	Water, RT
20	10	10	80	Mold	Air	Water, RT
30	10	20	70	Mold	Air	Water, RT
40	10	30	60	Mold	Air	Water, RT

Note: RT = room temperature.



LPP also hardens in moist air by the reaction of calcium hydroxide with atmospheric CO₂ to form calcite as shown in Eq. (3) and (4).



The aim of this study is to explore the effects of powder proportioning, water–binder ratio (w/b), fineness of lime, and curing conditions on the early strength of LPP. The total amount of pozzolana in the paste is limited to 40% in order to observe the effects of carbonation of free lime on strength development.

2. Experimental work

2.1. Materials

NHL in accordance with ASTM C821 was used. FA produced in accordance with ASTM C618 was supplied by Formosa Petrochemical Corporation, Taiwan. Type I PC in accordance with ASTM C150 was used to prepare control specimens. SF was supplied by Elkem Materials, China. The properties of the powders are given in Table 2. A polycarboxylated superplasticizer (SP) in accordance with ASTM C 494 type G admixture was used.

2.2. Sample preparation

Densities of the raw materials used in this study were determined in accordance with ASTM C 188. Weights of the desired NHL, FA, SF, and water were calculated by predetermined proportions of the total mass of powder. The mixing proportions of the powders are given in Tables 3 and 4.

SF, FA and PC were used as supplied, but NHL was sieved by ASTM #50 sieve to remove hard lumps and sintered particles. Some NHL was sieved through ASTM #30, #50, #100 and #200 sieves in order to obtain different particle size fractions. The materials required to make each mix were weighed to the nearest gram. A paddle mixer shown in Fig. 1(a) was used for mixing. The water was added to the pan followed by SF and FA. The pozzolanas were mixed to produce a uniform paste as shown in Fig. 1(b). NHL was then added to the pozzolana paste in three equal portions, and each addition was followed by mixing at low speed of 140 rpm to produce a uniform paste. A stiff paste as shown in Fig. 1(c) was formed and drops of SP were added while mixing at low speed to bring the paste to imminent flow, as shown in Fig. 1(d). The paste was then mixed at high speed of 245 rpm for one minute. SP dosages were varied with the paste proportions and w/b but less than 0.5% of the total weight of powder. In general, an increase in w/b or FA reduced the amount of SP required to provide the target workability. The paste was used to cast test cylinders with 50-mm in diameter and 100-mm in height.

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