Effect of incorporating hydrated lime on strength gain of high-volume fly ash lightweight concrete

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Abstract. High-volume fly ash concrete, HVFALC, may acquire popularity as durable, resource-efficient, and option of sustainability for different applications of concrete. The Pozzolanic reaction between fly ash, Ca(OH)₂ and water is the cause of making high-volume fly ash concrete a promising sustainable material. The aim of this study is to enhance the rate of the Pozzolanic reaction by incorporating external source of hydrated lime in the mix by two approaches. The first is to replace 10% by weight of the cementitious materials with hydrated lime and second is to use a lime-saturated water, with a concentration of 3g/L, for mixing. Two high-volume fly ash concrete mixes, with 50 and 60 % replacement by weight of cement, were included in this study. The testing program included water absorption, dry density, compressive and splitting tensile strengths. The testing program was extended to the age of 120 days. The present results showed that both approaches have caused an increase, ranging between 10 and 24 %, in absorption values and a slight reduction, less than 3 %, in dry density values. Both approaches have caused a significant gain in compressive and splitting tensile strengths. Replacing 10 % by weight of the cementitious materials with hydrated lime caused better enhancement in compressive and splitting tensile strengths for all curing ages than using lime-saturated water in mixing. The former approach was more effective for mix FA60 than for FA50 and the higher fly ash content in the FA60 mixes could be the reason.

Keywords: High-volume fly ash, hydrated lime, Lightweight concrete, Porcelanite

1. Introduction
Concrete production is rapidly increasing because of the low cost of the concrete structures in materials, concrete construction and maintenance [1]. Meyer [2] stated that the yearly production of concrete in the world is higher than ten billion tons. For manufacturing, this quantity of concrete more than 0.9 billion tons of Portland cement, 5 billion tons of aggregate and 0.6 billion tons of water are needed [3]. Lee and Wang [4] have suggested an equation to evaluate the total dioxide carbon emission from manufacturing process of one cube meter of concrete. They reported that the total CO₂ emission during manufacturing of one cubic meter of concrete include 300 kg, 890 kg, 970 kg and 150 kg of cement, sand, gravel and water, respectively is around 287 kg. Portland cement is responsible for about 0.93 % of CO₂ emission. Therefore, replacement of cement by high-volume of by-product materials such as fly ash in production of concrete will be more useful for cost, energy consumption, CO₂ emission, durability and low permeability [5].
Jow et al. [6] reported that the global production of fly ash was about 777 million tons in 2008, and just 54% was used. Wang et al. [7] declared that discarding this large quantity of fly ash would cause air pollution, destruction of green environment, and dust. Popular percentage of using fly ash in concrete is between 15-35% as a partial replacement by weight of Portland cement [8, 9]. The pozzolanic reaction occurs between Ca(OH)$_2$ coming from hydration of cement with silicate and/or aluminate in fly ash to produce calcium silicate hydrate and calcium aluminate hydrate [10].

The use of high-volume fly ash in traditional concrete has been studied over the last thirty years [11], while there are a few information available related with the properties of structural high-volume fly ash lightweight concrete.

The aim of this study is to enhance the rate of the Pozzolanic reaction by incorporating external source of hydrated lime in the mix by two approaches. The first is to replace 10% by weight of the cementitious materials with hydrated lime and second is to use a lime-saturated water, with a concentration of 3g/L, for mixing.

### 2. Materials & Experimental Work

**2.1. Materials**

2.1.1 *Portland cement.* An ordinary Portland cement Type I produced by Bazain cement factory was used in this work. Chemical analysis and results of physical tests are shown in tables 1 and 2, respectively.

#### Table 1. Chemical analysis of the used materials

| Chemical configuration | Content % |
|------------------------|-----------|
|                        | Cement    | Fly ash | Porcelanite | Hydrated lime |
| SiO$_2$                | 19.98     | 61.4    | 52.36       | 2.29         |
| CaO                    | 62.47     | 2.24    | 10.19       | 70.01        |
| MgO                    | 2.26      | 2.2     | 5.77        | 0.44         |
| Fe$_2$O$_3$            | 3.23      | 4.65    | 2.64        | 0.22         |
| Al$_2$O$_3$            | 4.98      | 25.78   | 12.34       | 1.07         |
| SO$_3$                 | 2.54      | 0.3     | 0.39        | 0.2          |
| Na$_2$O                | 0.3       | ----    | ----        | ----         |
| K$_2$O                 | 0.7       | ----    | ----        | ----         |
| L. O. I                | 3.02      | 3.29    | 16.30       | 22.66        |
| I. R                   | 1.22      | ----    | ----        | ----         |
| L. S. F.               | 0.977     | ----    | ----        | ----         |

#### Table 2. Physical properties of Materials

| Property                              | Results |
|---------------------------------------|---------|
| Specific Surface area                 | 3770    |
| (Blaine method, cm$^2$/gm)            |         |
| Soundness                             | 0.01    |
| (autoclave method)                    |         |
| Initial time of setting, hrs.:min.    | 2:40    |
| Final time of setting, hrs.:min.      | 4:00    |
| Compressive Strength                  |         |
| 3-days N/mm$^2$                       | 32      |
| 7-days N/mm$^2$                       | 38      |
2.1.2. **Fly ash**. Fly ash satisfying the requirements of ASTM C618 (Class F) [12] was used in this work. Its fineness, specific gravity, and activity index at 7 and 28 days are 3800 cm²/g, 2.59, 87%, and 93.5% respectively.

2.1.3. **Hydrated lime powder**. Local hydrated lime powder [Ca(OH)₂] used with 92.52% purity. The particles residue on 90µ sieve are 2.1%. It satisfied the requirements of IQS 807/2004 [13].

2.1.4. **Fine aggregate**. Local normal weight sand, used throughout this research, with grading satisfying the requirements of IQS 45/1984 zone 3 [14]. Its fineness modulus, specific gravity, and absorption are 2.67, 2.54, and 1.42%, respectively.

2.1.5. **Coarse aggregate**. Local Porcelanite stone was used as lightweight coarse aggregate. It was crushed and sieved to a maximum size of 19 mm to satisfy the requirements of grading of IQS 45/1984 [14]. Its SO₃%, specific gravity, and absorption are 0.39, 1.65, and 29.5%, respectively.

2.2. **Concrete mixes**
The selection of mix proportions for the lightweight concrete has been according to previous research [15] to have a minimum specified 28 days compressive strength of 28 MPa. Six mixes were produced. Two of them are reference mixes, FA50 and FA60. Two mixes were cast by using lime-saturated water, with concentration of 3g/L, as mixing water, FA50LW and FA60LW. Finally, mixes FA50L10 and FA60L10 were cast with 10% hydrated lime as partial replacement by weight of cementitious materials. Table 3 shows the details of the studied mixes. The average pH values for the used tap water and lime-saturated water are listed in table 4.

| Materials                        | FA50 | FA50 L10 | FA50 LW | FA60 | FA60 L10 | FA60 LW |
|----------------------------------|------|----------|---------|------|----------|---------|
| Water to binder ratio by weight  | 0.26 | 0.26     | 0.26    | 0.25 | 0.25     | 0.25    |
| Portland cement, kg/m³           | 327  | 294.3    | 327     | 261.6| 235.44   | 261.6   |
| Fly ash, kg/m³                   | 327  | 294.3    | 327     | 392.4| 253.16   | 392.4   |
| Hydrated lime, kg/m³             | 65.4 | 0        | 0       | 65.4 | 0        | 0       |
| Fine aggregate, kg/m³            |      |          |         |      |          | 475     |
| Coarse aggregate, Porcelanite, kg/m³ |      |          |         |      | 475      |         |
| HRWRA L/100kg of binder          |      |          |         |      | 1.48     |         |

**Table 4. Average pH values for tap and lime-saturated water**

| Type of water                          | pH value |
|----------------------------------------|----------|
| Tap water                              | 8.5      |
| Lime-saturated water with concentration of 3 g/L | 12.35 |

2.3 **Testing program**
The testing program was carried out according to the following specifications:
- Water absorption and dry density, ASTM C 642 [16].
- Compressive strength, BS EN 12390 [17].
- Splitting tensile strength, ASTM C78 [18].
Cubic specimens with the dimensions of 100×100×100 mm were cast for compressive strength test, and water absorption test. Meanwhile, cylindrical specimens with the dimensions of 100×200 mm
were cast for dry density and splitting tensile strength test. All specimens were water-cured according to the ASTM C192 [19].

3. Results and discussion

3.1. Water absorption and dry density
The results of water absorption and dry density of the studied HVFALC mixes are shown in table 5. The monitoring of these characteristics has been extended to the age of 56 days.

| Mix | Water absorption, %, at ages: | Dry density, kg/m³, at ages: |
|-----|--------------------------------|-------------------------------|
| F 8 7 | 4.5 | 1 | 11 | 1838 |
| F 9 7 | 4.6 | 1 | 11 | 1819 |
| F 1 8 | 4.7 | 1 | 11 | 1788 |
| F 9 7 | 5.2 | 1 | 11 | 1826 |
| F 1 9 | 6.0 | 1 | 11 | 1766 |

The following remarks have been recorded:
a) There were reductions in value of water absorption with the increase in curing age for all mixes. This observation could be explained by continuous hydration of cement and by Pozzolanic reaction. Another observation was that for the period of 28-56 days; the reductions have ranged between double to triple of those recorded in the period of 7-28 days of curing, as shown in figure 1. Moreover, the absorption values of 50% fly ash mixes were lower than those of 60% fly ash mixes. This may be attributed to the lower paste content of mixes with 60% fly ash content, which failed to cover all the porous Porcelanite particles.

b) Replacing 10 % by weight of the cementitious materials with hydrated lime caused an increase in absorption values for both mixes FA50L10 and FA60L10. This could be because hydrated lime has the lowest relative density if compared to cement and fly ash [ref]. The increase in absorption values was inversely proportional to the curing age and may be a result of the enhancement in Pozzolanic reaction.

c) Using lime-saturated water for mixing also resulted in increasing water absorption for mixes FA50LW and FA60LW and with higher values than the replacement approach.

![Reduction in Water Absorption, %](image)

Figure 1. Reduction values in water absorption at different ages for the studied HVFALC mixes

Figure 2 shows the development of dry density at different ages for the investigated HVFALC mixes and the following remarks could be concluded:

a) All mixes attained values less than 1900 kg/m³ at the age of 28 days, and therefore, they could be considered as structural lightweight concrete [20,21]. The progress of curing age caused considerable improvement in dry density values and that due to continuous hydration of cement and the pozzolanic reaction.

b) Both adopted approaches resulted in slight reductions for the dry density values, less than 3 %, when compared with the reference mixes, FA50 and FA60.
3.2 Compressive and splitting tensile strengths

Table 6 lists the results of compressive and splitting tensile strengths for curing ages of 7, 28, 56, 90 and 120 days. All mixes have passed the threshold of 21 MPa at 28 days for compressive strength and therefore, they represent structural lightweight concrete [20,21]. In addition, the strength values were positively proportional to the progress of curing time. Mix FA60 showed the lowest values of compressive and splitting tensile strengths and that is due to the lowest cement content.

Figure 3 shows the compressive strength development with curing time. The dotted lines in this figure refer to the mixes that included hydrated lime or mixed with lime-saturated water. Adopting the two approaches was useful in improving the Pozzolanic reaction; rate and value. For 28-day compressive strength, the gain was 9 and 14 % for mixes FA50L10 and FA50 LW, respectively, and 9 and 7 % for mixes FA60L10 and FA60 LW, respectively. Although the gain was reduced in later ages, i.e. 90 and 120 days, but it still was positive and significant. Replacing 10 % by weight of the cementitious materials with hydrated lime seems to be more beneficial in Pozzolanic reaction enhancement than using lime-saturated water in mixing. This enhancement was more obvious in FA60 mixes than FA50. The availability of fly ash in the former mixes could be the reason. Figure 4 illustrates the development of splitting tensile strength with age for the studied HVFALC mixes. The same concluded trends as for compressive strength results are highlighted here.

Table 6. Compressive and splitting tensile strength results for the studied HVFALC mixes.

| Mix    | Compressive strength, MPa, at ages: | Splitting tensile strength, MPa, at ages: |
|--------|-------------------------------------|------------------------------------------|
|        | 7d  | 28d | 56d | 90d | 120d | 7d  | 28d | 56d | 90d | 120d |
| FA50   | 21.0| 22.0| 28.0| 28.5| 30.8 | 1.42| 1.92| 2.30| 2.45| 2.80 |
| FA50L10| 20.5| 24.0| 29.0| 30.0| 32.0 | 1.40| 2.30| 2.40| 2.60| 2.88 |
| FA50WL | 20.5| 25.0| 29.0| 30.5| 32.5 | 1.48| 2.22| 2.38| 2.57| 2.83 |
| FA60   | 16.8| 21.5| 27.0| 27.0| 27.5 | 1.37| 1.91| 2.25| 2.27| 2.30 |
| FA60L10| 21.0| 23.5| 29.0| 29.0| 29.5 | 1.39| 2.28| 2.37| 2.50| 2.66 |
Figure 3. Compressive strength development with curing age for the studied HVFALC mixes.

Figure 4. Splitting tensile strength development with curing age for the studied HVFALC mixes.

4. Conclusions
This study aims to enhance the rate of the Pozzolanic reaction for high-volume fly ash lightweight concrete by incorporating external source of hydrated lime in the mix. Two approaches were investigated the first was to replace 10 % by weight of the cementitious materials with hydrated lime and second to use a lime-saturated water, with a concentration of 3g/lit, for mixing. Based on the results of the present investigation the following conclusions are drawn:

1. According to the attained density and 28-day compressive strength, all the produced HVFALC mixes are considered as structural lightweight concrete.
2. Replacing 10% by weight of the cementitious materials with hydrated lime and use of lime–saturated water both caused an increase in absorption values, ranging between 10 and 24%, for mixes FA50L10, FA60L10, FA50LW and FA60LW. The increase in absorption values was inversely proportional to the curing age and that may be a result of the enhancement in Pozzolanic reaction.

3. Both adopted approaches resulted in slight reductions in the dry density values, less than 3%, when compared with the reference mixes, FA50 and FA60.

4. Replacing 10% by weight of the cementitious materials with hydrated lime caused better enhancement in compressive and splitting tensile strengths for all curing ages than using lime-saturated water in mixing.

5. The enhancement, due to 10% by weight of the cementitious materials replacement, was more obvious in FA60 mixes than FA50. The higher fly ash content in the former mixes could be the reason.

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