Experimental evaluation of stress-strain relations in compression for Pozzolime concrete

T S al-Attar¹ S S Abdulqader² and R M Rashid³

¹ Professor, Civil Engineering Department, University of Technology, Baghdad, Iraq
² Assistant Professor, Civil Engineering Department, University of Technology, Baghdad, Iraq
³ MSc student, Civil Engineering Department, University of Technology, Baghdad, Iraq

Email: 40076@uotechnology.edu.iq

Abstract. World cement demand and production are increasing. This is associated with a significant increase in the cement industry’s absolute energy use and CO₂ emissions. With the increasing awareness about the environment, waste materials and by-products utilization, it has become an attractive alternative to obtain new solutions for a sustainable development. Pozzolime concrete is a promising binder alternative to Portland cement, which is forming compounds possessing cementitious properties. In this study the Pozzolime was produced via a mixture of hydrated lime and Pozzolana (Silica fume or fly ash). As a relatively new material, many engineering properties of Pozzolime concrete are still undetermined. Therefore, the modulus of elasticity and stress-strain behavior in compression have been studied experimentally. Two mixes were studied considering the compressive strength levels, 25 and 40, and for ages of 14, 28 and 56 days. The results obtained from experimental data were analyzed for stress-strain relations, compressive strength, $f_{\text{c}}'$, strain associated with peak compressive stress, $\varepsilon_p$, linearity of the stress-strain curve, modulus of elasticity of Pozzolime Concrete. An empirical equation is proposed for predicting stress-strain characteristics of Pozzolime concrete based on the test results by using regression analysis.

Keywords
Pozzolime, Compressive strength, modulus of elasticity, empirical equation.

1. Introduction
Concrete construction is the most adopted materials around the earth, and the essential ingredient in the production process is cement. A massive amount of anthropogenic carbon dioxide (CO₂) emits in the manufacturing process of cement, accounting for approximately 5 – 8 % of global emissions [1].

One of the solutions to reduce this effect is a substitutional binder replacement for cement by using supplementary cementations materials. Pozzolan-lime cements offer significant opportunities to incorporate green concrete as it is probable to hire an industry by-product to exceedingly replace the use of ordinary Portland cement in concrete [2].

Pozzolans or supplementary cementitious materials, epitome: Fly ash, Silica fume, Slag is undercover by-products of many industrial processes. Pozzolanic reaction is a chemical reaction resulting from finely grounded siliceous or siliceous aluminous phases existing in Pozzolan and calcium hydroxide Ca(OH)₂, which is a by-product of the formalization of calcium silicate hydrates CSH of Portland cements, to get compounds having cementitious properties [3].
One of the disadvantages of Lime-Pozzolan concrete is slow strength development with curing ambient temperature condition. In cold weather countries, there is urgent requirement for acceleration because of the delay in initial setting time and formwork dissociation. Meanwhile, set retardation in hot weather regions is an advantage and there is no need for retarders [4].

In Iraq, Kadum et al. [5] recently has developed and patented a sustainable binder called Pozzolime. This binder is a mixture of hydrated lime, fly ash and silica fume and includes no Portland cement. They conducted an extensive investigation for the characteristics of this binder, such as; heat of hydration, absorption, setting time, density, strength development and drying shrinkage.

Generally, the apparent stress-strain curve of concrete consists of ascending and descending parts. For the ascending part, which takes place first and occurs before reaching the peak stress, the rates of stress and strain are both positive. Meanwhile, for the descending portion, the strain rate is positive whereas the stress has negative rate [6]. The relation between stress and strain starts with linear mode to some extent and then the curve deviates from linearity due to micro-cracking and creep. Therefore, the factors most affecting this relation are the nature of concrete microstructure and the rate of application of stress [3]. However, the plotting of the ascending part is very useful in calculating the modulus of elasticity. This modulus plays a major role in all analysis and design formulae of concrete.

With regard to the behaviour of concrete under progressive compressive stress, four distinct stages could be distinguished. The specimen below the 30 percent of the ultimate load behaves elastically, in other words the $\sigma$-$\varepsilon$ curve remains linear because the cracks in the interfacial transition zone remain stable. With increasing stress above 30 percent of ultimate load, the $\varepsilon/\sigma$ ratio increases and the curve begins to deviate appreciably from a straight line. Also, the length, width and number of the micro-cracks in transition zone increases. With further increase in stress level, the crack system proliferation and propagation in matrix, cause a bend toward horizontal in the curve. The final stage, the rate of stress seems to reach the critical level and a rapid propagation of cracks in both the matrix and the interfacial transition zone. Following the peak strength, a progressive strain softening occurs [7].

Understanding the response of stress-strain behaviour of Pozzolime concrete in uniaxial compression loading is significant for successful analysis and design of structures. As a relatively new binder, many engineering properties of Pozzolime concrete are still undetermined.

The aim of this study is to carry out a systematic investigation about stress-strain relationships of Pozzolime concrete under uniaxial compression. The investigation included many related characteristics in analysis and discussion. These characteristics are: stress-strain behaviour, compressive strength, strains associated with peak stress, area under the curve and values of modulus of elasticity. Finally, an empirical equation to predict the modulus of elasticity was proposed.

2. Experimental work
2.1. Materials
The binder in this study consisted of fly ash (ASTM C 618-08) [8], silica fume (ASTM C1240-10) [9], hydrated lime (ASTM C 821) [10] and ordinary Portland cement (ASTM C150) [11]. The chemical analysis and fineness (Blaine) of these materials are shown in table 1. Crushed gravel with maximum size of 14mm, specific gravity (SSD) of 2.65, sulphate content of 0.06% and bulk density of 1565 kg/m³, was used as coarse aggregate. The fine aggregate was natural river sand. The main properties of this sand are; fineness modulus of 2.9, specific gravity (SSD) of 2.63 and sulphate content of 0.01%. Vislocete5390-L was employed as high-range water reducer (ASTM C494) [12] to control workability.
Table 1. Chemical properties and fineness of cement, hydrated lime, fly ash and silica fume

| Materials         | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO  | MgO  | SO₃ | Na₂O | K₂O | LOI | Fineness (Blaine), m²/kg |
|-------------------|------|-------|-------|------|------|-----|------|-----|-----|-------------------------|
| Cement, OPC       | 21.8 | 6.5   | 2.2   | 61.5 | 1.4  | 2.5 | 0.28 | 0.51 | 2.4 | 240                     |
| Hydrated Lime, HL | -    | -     | 65.3  | 0.123| -    | -   | -    | -   | -   | 1200                    |
| Silica fume, SF   | 94.58 | 3.24  | 0.06  | 0.58 | 0.22 | 0.11| 0.21 | 0.35 | 1.98 | 200000                  |
| Fly ash, FA       | 65.67 | 18.79 | 5.88  | 0.98 | 0.72 | 0.19| 1.35 | 2.99 | 3.1  | 773                     |

2.2. Mix proportions

Two mix proportions were considered to attain two specified compressive strength levels, 25 and 40 at 28 days. According to data published by Kadum et al. [5], the proportions listed in table 2 were adopted.

Table 2 Mix proportion details of used Pozzolime concrete

| Mix    | Binder, kg/m³ | Aggregate, kg/m³ | Water, kg/m³ | SP, % | W/B by wt. | A/B by wt. |
|--------|---------------|------------------|---------------|-------|------------|------------|
|        | OPC | HL  | FA  | SF  | Coarse Fine |
| M25    | 40  | 180 | 108 | 72  | 960 640    | 140 2 | 0.35 4 |
| M40    | 42.5| 191.25| 76.5| 114.75| 1000 700 | 119 3 | 0.28 4 |

2.3. Testing program

The following tests were conducted on cylindrical specimens with dimensions of d = 150 mm and h = 300 mm at ages of 14, 28 and 56 days. All specimens were water-cured (ASTM C192) [13] till the age of test:
- Dry density (ASTM C642) [14]
- Compressive strength (ASTM C39) [15]
- Chord modulus of elasticity (ASTM C 469) [16]

3. Results and discussion

3.1. Stress-strain behaviour of Pozzolime concrete

The stress-strain relation for Pozzolime concrete mixes M25 and M40 at different curing periods are presented in table 3 and depicted in figure 1.

The main observation is that the E value for Pozzolime develops slower with time than Portland cement concrete and that is mainly due to the slow rate of Pozzolanic reaction.

With respect to the linearity limit of the relation, the value of 0.45 \( \sigma_p \) could be considered as an upper limit whereas after this value the curves shown in figure 1 starts to deviate from linear relationship. Therefore, it could be concluded that Pozzolime has a similar behaviour to that of Portland cement concrete under compression stress.
Table 3. The density, peak stress, strain associated with peak stress and modulus of elasticity for the studied Pozzolime mixes

| Mix  | Age, day | Density, kg/m³ | σₚ, MPa | ε₀, | Eₑₓₚ, GPa | 0.45 σₚ, MPa |
|------|----------|----------------|---------|----|----------|--------------|
| M25  | 14       | 2209           | 17.6    | 0.003143 | 5.60      | 7.92         |
|      | 28       | 2187           | 26.5    | 0.003560 | 7.45      | 11.93        |
|      | 56       | 2062           | 41.8    | 0.003237 | 15.36     | 18.81        |
| M40  | 14       | 2235           | 27.6    | 0.003078 | 8.96      | 12.42        |
|      | 28       | 2305           | 39.7    | 0.002990 | 13.77     | 17.87        |
|      | 56       | 2271           | 70.6    | 0.002500 | 28.25     | 31.77        |

Figure 1. Compressional stress-strain relations for Pozzolime concrete mixes at different strength levels and ages.
3.2. Strain associated with peak stress, $\varepsilon_p$

The $\varepsilon_p$ of Pozzolime concrete mixes at ages of 14, 28 and 56 days are presented in Table 3. At 28-day, the recorded strain values were 0.00299 and 0.00356 for mixes M25 and M40, respectively. As shown in Figure 2, the present results revealed that the values of $\varepsilon_p$ are inversely proportional to $\sigma_p$. This trend implies that higher strength Pozzolime has lesser extensibility than mixes with lower strength. This conclusion is in agreement with Setunge and Attard work for Portland cement concrete [17].

![Figure 2. The relationship between peak stress and associated strain for the studied Pozzolime mixes](image)

Table 4. Expressions for modulus of elasticity by international models.

| Reference         | Expression                                                                 | Units                                      |
|-------------------|-----------------------------------------------------------------------------|--------------------------------------------|
| AS 3600 [18]      | $E = \rho^{1.5} \left( 0.024 f'_c^{0.5} + 0.12 \right)$                    | $E$ (MPa), $f'_c$ (MPa), $\rho$ (kg/m$^3$) |
| Eurocode 2 [19]   | $E = 22 \left( f'_c / 10 \right)^{0.3}$                                   | $E$ (GPa), $f'_c$ (MPa)                    |
| ACI 318-14 [20]   | $E = 4700 \left( f'_c \right)^{0.5}$                                     | $E$ (GPa), $f'_c$ (MPa)                    |
| CEB-FIP 2010 [21] | $E = 21500 \left( f'_c / 10 \right)^{1.3}$                                | $E$ (MPa), $f'_c$ (MPa)                    |

Table 5. Predictions of the international models for the studied Pozzolime mixes

| Mix   | Age, day | Modulus of elasticity, GPa, according to: |
|-------|----------|--------------------------------------------|
|       |          | Exp. present work | ACI 318-14 [20] | Eurocode 2 [19] | AS3600 [18] | CEB-FIP 2010 [21] |
| M25   | 14       | 5.60            | 19.72           | 26.07            | 22.91         | 25.96            |
|       | 28       | 8.96            | 24.69           | 29.83            | 25.99         | 30.16            |
|       | 56       | 7.45            | 24.18           | 29.46            | 24.90         | 29.74            |
| M40   | 14       | 13.77           | 29.61           | 33.27            | 30.00         | 34.04            |
|       | 28       | 15.36           | 30.38           | 33.78            | 25.77         | 34.63            |
Figure 3. The predictions of the international models for the Pozzolime mixes in the present study.

All the employed models have overestimated the actual E values for the studied mixes. Therefore, a proposed formula was presented, which was based on linear regression analysis for the present test results:

\[ E = 5571.6 f_{c}^{0.5} - 19979 \quad R^2 = 0.9684 \]  

[1]

4. Conclusions

Based on the results of the present experimental work, the following conclusions have been drawn:

1. With respect to the linearity limit of the stress-strain relation, the value of 0.45 \( \sigma_p \) could be considered as an upper limit and Pozzolime has a similar behaviour to that of Portland cement concrete under compression stress.
2. At 28-day, the recorded \( \varepsilon_p \) values were 0.00299 and 0.00356 for mixes M25 and M40, respectively.
3. The present results revealed that the values of \( \varepsilon_p \) are inversely proportional to the \( \sigma_p \). This trend implies that higher strength Pozzolime has lesser extensibility than mixes with lower strength.
4. Most of the known international models have overestimated the actual E values for the studied mixes. Therefore, a proposed formula is presented, which is based on linear regression analysis for the present test results.

References

[1] McCaffrey R 2002 Glob. Cem. Lim. Mag. Sp. Iss. 15
[2] Grist E R, Paine K A, Heath A, Norman J and Pinder H 2015 Clea. Prod. 93 p 26
[3] Neville A M 2011 Properties of Concrete 5th ed. Prentice Hall UK
[4] Allahverdi A and J Ghorbani 2006 Ceramics 50 p 193
[5] Kadum N M, al-Attar T S and Al-Azzawi Z M 2017 MATEC 120 1
[6] Slate F O and Hoover K C 1984 Frac. Mech. Conc. 5 137
[7] Mehta P K and Monteiro J M 2006 Concrete-Microstructure 3rd ed. USA
[8] ASTM C 618 2015 04.02 1
[9] ASTM C 1240 2015 04.02 1
[10] ASTM C 821 2015 04.02 1
[11] ASTM C 150 2015 04.02 1
[12] ASTM C 494 2015 04.02 1
[13] ASTM C 192 2015 04.02 1
[14] ASTM C 642 2015 04.02 1
[15] ASTM C 39 2015 04.02 1
[16] ASTM C 469 2015 04.02 1
[17] Setunge M M and Attard S 1996 ACI Mater. J. 93 432
[18] Australian Standard 2005 AS3600 Australia
[19] Eurocode-2 2004 ENV
[20] ACI Committee 318 2014 American Concrete Institute USA
[21] CEB-FIP 2010 Model Code 1 117.