Modeling the cementitious effect of the Pozzolana on the compressive strength of concrete

Afif Rahma and Haifaa Jomaa

Cogent Engineering (2018), 5: 1548002
Modeling the cementitious effect of the Pozzolana on the compressive strength of concrete
Afif Rahma1* and Haifaa Jomaa2

Abstract: The natural Pozzolana is a siliceous material (SiO2) that reacts with the calcium hydroxide Ca(OH)2 produced during the hydration period of the cement; this inherent feature increases the cementitious property of the grout and improves the compressive strength of the concrete. However, the necessary amount of this material in the concrete composition remains the subject of research to find the adequate rate to meet the expected strength of concrete. In this study, authors investigate the cementing properties of a local Pozzolana called “Tal Shihan” and quantify its role on the compressive strength of cement. Accordingly, to better isolate the effect of Pozzolana from that of cement, two series of batches were formulated for 350 and 400 kg amount of cement of per cubic meter, with a successive increase of the Pozzolana by a rate of 2.5% of the cement weight. Regression analysis was performed that relates the compressive strength versus the Pozzolana rates tested. The results of this study indicate the ability of Pozzolana to improve the compressive strength of concrete. This happens as Pozzolana accelerates the hydration reaction of concrete between the ages of 28–56 days, increasing its strength that is expected normally over the time.

Subjects: Quality Control & Reliability; Engineering Mathematics; Composite Materials; Stress Analysis; Engineering Project Management; Composites; Nanoscience & Nanotechnology; Technology; Concrete & Cement

ABOUT THE AUTHOR
Afif Rahma, is a faculty member at Damascus University in Syria, currently Professor at Al-Ahliyya Amman University in Jordan. He has had the Ph.D. in Soils-Structures Mechanics in 1991 of Ecole Centrale Paris.

The behavior of the granular medium was the axis of his research where the numerical simulation and the statistical modeling made a part. Later, the research field was oriented towards the concrete, where the cementitious materials intervene. The development of the concrete mix design has been part of his scientific interest that to satisfy the concrete production and the construction requirements. He worked for some ready mixed concrete societies. Meanwhile, this exciting scientific field has encouraged the author to supervise many research works to examine the evolution of the concrete properties by adding additional materials to the concrete mixture as the glass powder, the metallic fibers, the Pozzolana; where, this paper is a part of his scientific activity.

PUBLIC INTEREST STATEMENT
The divergence of interest, between the cost of production and the legislation of the environmental protection, is one of the main concerns of construction activities; hence, This question arises with the demands of the urban development that require an increase of the cement production, which is accused of its contribution to the atmospheric pollution in CO2.

In the spirit of solving this problem, the researchers have interested to find materials that help to settle, at the same time, the issue of the pollution and the cost of construction. Thus, the Pozzolan meets this objective. It is a natural material, found in nature in its pure state and considered as a green material.

This paper shows the results of an experimental work on a local Pozzolana blinded with concrete. The study achieved a statistical analysis and proposed mathematical models to manage its use in the concrete mix design.
Keywords: concrete; Pozzolana; compressive strength; modeling; aggregate composition

1. Introduction

The natural Pozzolana is a volcanic ash, classified in the group of siliceous ($\text{SiO}_4$) or aluminous-siliceous material, which inherently possesses a cementitious characteristic, wherein the stage of Cement hydration process the Pozzolana reacts with the calcium hydroxide $\text{Ca(OH)}_2$ (i.e., lime) to form cementitious properties (ACI 232.1R-00). This reaction is expressed, in a chemical abbreviation, by calcium–silicate–hydrate ($\text{C}_x\text{S}_y\text{H}$) (Chappex & Scrivener, 2012a).

The presence of the alkalis in the cement serves the Pozzolana to mitigate the reaction of the cement in the concrete grout. It first starts to moderate the hydration temperature and so reduce the rate of alkali sulfate reaction (ASR), occurring between the alkali hydroxide constituents (sodium $\text{Na}_2\text{O}$ and potassium $\text{K}_2\text{O}$) available in cement and the reactive silica minerals available in aggregates (Pan, Feng, Sun, Zhang, & Owen, 2012; Chappex & Scrivener, 2012b).

Consequently, the moderation of the hydration oxide temperature limits the swell of calcium–silicate–hydrate ($\text{C}_x\text{S}_y\text{H}$) which causes, in the presence of water, an increase in volume of concrete; in turn, it exerts an expansion pressure inside the hardened concrete, causing the deterioration and the loss of strength, so finally leading to damage the hardened concrete medium. (Wedding & Bhatty, 1985; Rajabipour, Giannini, Dunant, Ideker, & Thomas, 2015).

These chemical characteristics of Pozzolana are advantageous for concrete batches, where the reaction Pozzolana-Cement contributes to improving the workability of fresh Concrete (Gh., Alkadi, & Asteris, 2013; Senhadji, Escadeillas, Khelafi, Mouli, & Be-Nosman, 2012) and to increase the bearing capacity and the durability of hardened concrete (Setina, Gabrene, & Juhnevica, 2013).

For all of these appropriate characteristics of Pozzolana, this raw material is often added to the Portland Cement to improve the mechanical properties of concrete (Thomas, 2011).

Various studies have confirmed the cementitious features of Pozzolana and its ability to improve the strength of concrete. This work has given interest, to quantify the role of the Pozzolana and to show the feasibility to develop mathematical models that are able to predict the contribution of this natural material to improve the strength of concrete.

2. Significance of research

The cement in Syria suffers serious fluctuations in its mechanical properties, due to the lack of standardization of the production system, the unsuitable control of the storage, the absence of follow-up and the maintenance of furnaces. Consequently, the engineer, typically, takes excep- tional measures, such as the use of chemical additive or other cementitious materials like the fly ash, to acquire the required strength of concrete.

Consequently, the investment of the natural Pozzolana attracts the public service and the ready mixed concrete plant, in order to explore this natural material to improve the properties of concrete (Alp, Süngün, Yilmaz, Kesimal, & Yilmaz, 2009; Haral & Haral, 2013).

Moreover, the concrete industry attempts to expand the use of Pozzolana as a way to reducing the cost of construction work thus to reducing the public and private expenditure; furthermore, it considered as a solution to reduce the emission of the pollutant $\text{CO}_2$, accompanying the cement production (Edwin & Dunstan, 2011).

The mineralogical study of “Tal Shihan”, available in the south of Syria, showed an enormous quantity of Pozzolana considered as natural “green material” which can serve to improve the specification of the local cement and thus the concrete mixture and to meet the economic imperatives and the environmental requirements.
In the context of modeling the effect of Pozzolana on the compressive strength of concrete, this research has followed a procedure, which allowed to distinguish the contribution of Pozzolana from that of cement and to better control the use of this natural material to improve the compressive strength of concrete.

3. Test methodology
The main idea was to preserve the amount of Cement constant and vary the rate of the Pozzolana in the batches of concrete. This process aimed to distinguish between the role of the cement and the contribution of the Pozzolana to the development and the improvement of the compression strength of concrete.

Hence, the batch of materials was enough for the sets of tests that were carried out under the same conditions, to make sure the homogeneity, which so made it possible to focus only on the effect of cement and the Pozzolana.

To calibrate the effect of the Pozzolana on the compression strength of concrete, relatively to the amount of cement, two control mixtures were prepared with 350 and 400 kg/m$^3$ of Cement.

Finally, the results of the compression test of the concrete samples, with and without Pozzolana, were analyzed to develop a wide perspective about the effect of the Pozzolana on the compression strength of concrete.

4. Materials and method

4.1. Aggregates
The mineral Dolomite in Syria is the dominant rock used for coarse and medium aggregates as well as the crushed sand, while the composition of the natural sand is for about 60–70% of silicate; the (Table 1) shows the characteristic properties of aggregates.

4.2. Cement and Pozzolana specifications
The natural Pozzolana in form of grains was milled into powder for maximal size of 600 µm, where the passing weight from the sieve of 300 µm size constitutes 95% of the powder; hence, the passing particles from the sieve of 200 µm size was in the order of 18.5%.

Meanwhile, the Cement and the Pozzolana specifications were defined according to ASTM C188.95 and ASTM C204-00, where the laboratory tests gave the values of 2.9 g/cm$^3$ for the specific gravity, 4200 cm$^2$/g for the specific surface area (Blaine Test) and 1.6% for the rate of absorption. The cement was the OPC type I, specified by 3.15 g/cm$^3$ for the specific gravity and 3200 cm$^2$/g for the specific surface area.

Moreover, the Pozzolana compared with 8 control samples of cement, according to the “Activity Method” (EN 196–5), where the test results gave the value of 96% for the “Activity Index”; Figure 1 shows the solubility curve of CaO concentration with [OH$^-$] concentration.

Furthermore, the X-ray method gave the chemical composition of the Cement and the Pozzolana as shown in the (Table 3).

4.3. Mixture batches
Two control batches were prepared for 350 and 400 kg/m$^3$ of Cement (Table 4), the aggregate distribution of the concrete mixtures (Figure 2) was proportioned for a fineness factor of 4.8 with 6% of fines particles (# 200), and a percentage of Sand/Coarse ≈ 1, (ACI 91-M92, 1994).

The W/C ratio was 0.6 and 0.55, respectively, for the 350 and the 400 kg Cement, to assure an adequate workability; accordingly, the Abrams cone test gave an approximate slump of 10.5–11 cm, respectively, for the two batches, see (Table 3).
| Material          | Nominal size | Dry specific gravity OD | Absorption | Sand equivalence | Loss-Angeles | Proportion rate |
|-------------------|--------------|-------------------------|------------|------------------|--------------|----------------|
| Coarse            | 19–12        | 2787                    | 0.45       | –                | 18           | 32.3           |
| Medium            | 12–4.75      | 2751                    | 0.47       | –                | 18           | 20.8           |
| Crushed sand      | <4.75        | 2723                    | 1.46       | 75.3%            | –            | 42.7           |
| Natural sand      | 1            | 2615                    | 2.29       | 82.8%            | –            | 4.2            |
The Pozzolana was added to the control mixtures by order of 2.5%, 5%, 7.5%, 10%, 12.5%, 15% of the cement weight. Besides, the Pozzolana was considered in the mixture design as part of the aggregates. Nevertheless, the weight analysis of the batches (Table 2) showed an inconsiderable modification of the aggregate’s weight, where the rate of Pozzolana did not exceed 2.07% of aggregates weight and 2.46% of the concrete volume in the extreme cases of 15% Pozzolana for 400 kg cement/m³).

4.4. Sampling and laboratory test
To follow the evolution of compression strength over the time, 18 cubic samples of 15 cm were taken for each batch. In total, 252 samples were cured for 24 h, then conserved in the water with a temperature of 23 ± 2°C according to ASTM-192 recommendation (ASTM C 192/C 192M, 1994), then tested on compression test at ages of 3, 7, 28, 56, 100 and 180 days.

5. Results and discussion
The results of the compression test were converted to characteristic strength value (cylindrical value).
The compression strength value at age \( t \) of Pozzolana \( n \) and the variables \( t \) and \( n \).

5.1. Modeling the role of Pozzolana

The relationship between the compression strength, for the 350 and 400 kg amounts of cement and the different rates \( n \) of Pozzolana at the different ages \( t \) of concrete are presented in Figure 3(a–b). Thereafter, the values of compression strength \( \sigma \) were analyzed by the linear regression method which has shown a significant relationship between the strength value of \( \sigma \) and the variables \( n \) and \( t \).

\[
\sigma(t) = \sigma_0 + n_\eta(t) \text{ (Mpa)}
\]

where:

- \( \sigma(t) \): the compressive strength value at age \( t \) for a rate of Pozzolana \( n \).
- \( \sigma_0(t) \): the compressive strength value at age \( t \) in case zero amount of Pozzolana \( n = 0 \).
- \( \eta(t) \): the coefficient of regression depends on the concrete age.
So, the first term of Equation (1) represents the value of $\sigma_0$ (of the control mix: $n = 0$), the second term $\eta(t)$ represents the increase factor of the compressive strength, it depends on the age ($t$) and the rate of Pozzolana ($n$) where $n$ varies from 0 to 1.
Although the value of $\sigma_0(t)$ could be expressed by the logarithmic equation (Figure 4):

$$\sigma_0(t) = A \ln(t) + B + n \eta(t) \text{ (Mpa)}$$ (2)

where $\sigma_0(t)$ varies towards a constant value at long-age (about 2 years for the 350 kg cement).

$A$ and $B$: constants parameters related to the quantity of cement as shown in Figure 4.

While $\eta(t)$, (Figure 5), could be given by Hoerl Model (Hoert & Snee, 2012; CurveExpert 1.4 Software):

$$\eta(t) = 7.2(0.99^{0.49})t^{0.49} \quad R^2 = 0.98 \quad \text{for 350 kg/m}^3$$ (3)

$$\eta(t) = 2.6(0.98^{0.7})t^{0.7} \quad R^2 = 0.98 \quad \text{for 400 kg/m}^3$$ (4)

Referring to Figures (3 and 5), the hardening process in presence of Pozzolana showed two phenomena. The first one is the slow evolution of the compression strength in the early days of hardening, which was recovering again with time. The second one is the similarity of the strength development for the 350 kg and the 400 kg cement.

Meanwhile, an inverse relationship between the contribution of the Pozzolana and the amount of cement in the batches manage the hydration and the hardening process of concrete, where the

**Figure 4.** Evolution of the compression strength $\sigma_0$ over the time. Results of the control mix without Pozzolana ($n = 0$).

**Figure 5.** Evolution of the parameter $\eta$ over the time for the rate $n = 1$ of Pozzolana. The effective value of $\eta$ is factored by the used rate $n\%$ of Pozzolana.
The contributing of the same rate of Pozzolana is more distinguished for the 350 kg cement than for the 400 kg cement.

The mathematical term \( \eta(t) \), showed in Figure (5) and expressed by Equations (3 and 4), draw the way of the hydration and the reaction between the cement and the Pozzolana. Accordingly, the effect of the Pozzolana over the time is not linear but varies significantly during the hydration periods.

The delaying of reaction on the first time of hardening, for the two batches (Figure 3(a and b)), is interpreted by the presence of the alkalis in the cement, which served the Pozzolana to mitigate the cement hydration and delay the alkali sulfate reaction (ASR).

Thus, the ASR reaction attenuates the hydration process in the earlier period of the hardening, but this effect decreases slowly over the time to allow the resumption of the hydration, which significantly increased the compression strength of concrete, to reach its maximal value in the period of 28-56 days. This stage is followed by a slowing down-stage up to the age of one year for the 400 kg/m^3 and about two years for the 350 kg/m^3.

However, the inverse relationship between the cement and the contribution of the Pozzolana on the strength of concrete, for the 350 and that of the 400 kg cement, is explained by the role of the required water in the concrete batches. The excess amount of the needed water required to assure the workability is captured by the amount of Pozzolana added to the concrete batches; this act is justified by the decrease of workability defined by Abrams test (Figure 6).

Nevertheless, after the first period of hardening, the captured amount of water reintegrates again in the hydration process to help and develop efficiently the reaction (C-S-H) in the case of the 350 kg cement less for the 400 kg; consequently, a better reintegration and contribution of Pozzolana in case of the 350 kg than for the 400 kg cement.

### 5.2. Modeling the effect of the W/(C+P) ratio

Often, the interest directs towards the relationship between the compressive strength of concrete and the (water/cementitious materials) ratio, especially at age of 28 days; however, it seems interesting to see the deep relationship between these two values at long-age.
Figure 7 illustrates, by the linear regression method, the relationship between the compressive strength and the ratio $\theta = W/(C + P)$ according to the age ($t$) of concrete, where ($W$) the required water, ($C$) is the amount of cement and ($P$) the amount of Pozzolana used in the concrete batches.

Therefore, the regression analysis of the experimental results (Figure 7) confirms the associate role of the cementitious materials ($C + P$), well as the relationship between the ratio ($W/C + P$) and the concrete strength. The effect of the cementitious materials is justified by the superposition and the convergence of the compression strength value of the 350 and 400 kg cement, for $\theta = 0.52$ to 0.55.

Thus, Equation (5) draw the contribution of the cementitious materials ($C + P$), where the value of the concrete strength at age ($t$) is depends on the variable $\theta = W/(C + P)$

$$\sigma(t) = \sigma_0(t) - \lambda(t) \cdot \ln(\theta)$$  \hspace{1cm} {\text{(5)}}

The value of $\sigma_0$ and $\lambda$ extracted from the equations of the regression lines (Figure 7); where $\sigma_0$, the strength of concrete without Pozzolana, and $\lambda$ is the intensity factor of the $W/(C + P)$ ratio, in turn ($C + P$), to the strength of concrete.

Thus, the evolution of $\sigma_0$ value and $\lambda$ value, with the time ($t$), are formulated, by Hoerl Model (Figure 8), to take the following form:

$$\sigma_0(t) = 28.7(0.997^t)t^{0.238} \text{ (Mpa)}$$  \hspace{1cm} {\text{(6)}}

$$\lambda(t) = 28.7(0.995^t)t^{0.256} \text{ (Mpa)}$$  \hspace{1cm} {\text{(7)}}

Checking the previous relations (5, 6 and 7), the value of the effective strength $\sigma(t)$ takes a hypothetical value when $t = \infty$ (practically more than a year), which concords with the experimental results and prove the validity of the models.

6. Conclusion

The experimental results have shown the inherent properties of “Pozzolana Tal Shihan” and its ability to improve the compressive strength of concrete, consequently its potential to reduce the cost of production.

However, the statistical analysis has proven the possibility of predicting the effect of Pozzolana, and its contribution beside cement, by simple mathematical models wherein the variables, which
intervene to control the evolution of the compression strength, was the amount of cement, the rate of Pozzolana and the age of concrete.

Moreover, the experimental results, justified by the mathematical modeling, have proven that after the first period of hydration, the Pozzolana accelerates the hydration reaction and offers the concrete, between the ages of 28–56 days, an increase of strength expected normally over the time.

Acknowledgements
This study has been realized as a research project at Damascus University for which we show all loyalty.

Funding
The authors received no direct funding for this research.

Author details
Afif Rahma1
E-mail: a.rahma@ammanu.edu.jo
E-mail: prf.afif.rahma@gmail.com
ORCID ID: http://orcid.org/0000-0002-9957-3241
Haifaa Jomaa2
E-mail: haifaa.jomaa@gmail.com
1 Department of Civil Engineering, Faculty of Engineering, Al-Ahliyya Amman University, Al Salt-Jordan, 19328.
2 Structure Department, Faculty of Civil engineering, Damascus University, Syria.

Cover Image
Source:
Citation information
Cite this article as: Modeling the cementitious effect of the Pozzolana on the compressive strength of concrete, Afif Rahma & Haifaa Jomaa, Cogent Engineering (2018), 5: 1548002.

References
ACI. (1994). ACI Material Journal Title No. 91-M92. Use of raw or processed natural Pozzolans in concrete. Reported by American Concrete Institute Committee 232. 77 1093–1099. doi:10.3168/jds.S0022-0302(94)70704-2
Alip, I., Sungun, D. H., Yilmaz, Y. H., Kesimal, A. O., & Yilmaz, E. (2009). Pozzolanic characteristics of a natural raw material for use in blended cement. Iranian Journal of Science & Technology, Transaction B, Engineering, 33(8A), 291–300.
ASTM C 192/C 192M. (1994). Standard practice for making and curing concrete test specimens in the laboratory. West Conshohocken, PA: American Society for Testing and Materials.
Chappex, T. H., & Scrivener, K. (2012a). The influence of aluminium on the dissolution of amorphous silica and its relation to alkali silica reaction. Cement and Concrete Research, 42(12), 1645–1649. doi:10.1016/j.cemconres.2012.09.009
Chappex, T. H., & Scrivener, K. (2012b). Alkali fixation of C–S–H in blended cement pastes and its relation to alkali silica reaction. Cement and Concrete Research, 42(8), 1049–1054. doi:10.1016/j.cemconres.2012.03.010
Edwin, R., & Dunstan, J., (2011). How does Pozzolanic reaction make concrete green? World of Coal Ash (WOCA) Conference, Denver, CO, USA.
Gh., A.-C., Alkadi, K. M., & Asteris, P. G. (2013). Natural pozzolana as a partial substitute for cement in concrete. The Open Construction and Building Technology Journal, 7, 33–42. doi:10.2174/1874836801307010033
Haral, M. N., & Haral, M. A. (2013). Influence of natural pozzolan on proprieties of self-compacting concrete. (Thesis). King Saud University.
Hoert, R., & Snee, R.D. (2012). Statistical thinking: Improving business performance (2nd ed.).New Jersey, NJ: John Wiley & Sons. ISBN-13: 978-1118094778
Pan, J. W., Feng, Y. T., Sun, Q. C., Zhang, C. H., & Owen, D. R. (2012). Modeling of alkali-silica reaction in concrete: A review. Frontiers of Structural and Civil Engineering, SSN: 2095-2430 (Print) 2095-2449. 6(1), 1–18.
Rojabipour, F., Giannini, E., Dunant, C., Ideker, J. H., & Thomas, M. (2015). Alkali–Silica reaction: Current understanding of the reaction mechanisms and the knowledge gaps. Cement and Concrete...
Senhadji, Y., Escadeillas, G., Khelafi, H., Mouli, M., & Be-Noorman, A. S. (2012). Evaluation of natural pozzolan for use as supplementary cementitious material. *European Journal of Environmental and Civil Engineering*, 16(1), 77–96. doi:10.1080/19648189.2012.667692

Setina, J., Gabrene, A., & Juhnevica, I. (2013). Effect of pozzolanic additives on the structure and chemical durability of concrete. *Procedia Engineering*, 57, 1005–1012. doi:10.1016/j.proeng.2013.04.127

Thomas, M. (2011). The effect of supplementary cementing materials on alkali-silica reaction: A review. *Cement and Concrete Research*, 41(12), 1224–1231. doi:10.1016/j.cemconres.2010.11.003

Wedding, P.A., & Bhatty, M. S. Y. (1985). Mechanism of Pozzolanic reactions and control of alkali-aggregate expansion. *ASTM International, Cement, Concrete and Aggregates*, 2(7), 69-77. doi:10.1520/CCA10372J