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Optimum usage of a natural pozzolan for the maximum compressive strength of concrete

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Abstract

Pozzolans provide an economic production possibility in the concrete industry and improve the properties of concrete, such as durability. Effects of a pozzolan on the properties of concrete vary with the pozzolan type and volume.

In this study, effect of a natural pozzolan on the properties of concrete was investigated. Fifteen concrete mixtures were produced in three series with control mixes having 300, 350 and 400 kg cement content. These control mixes were modified to have a combination of 250, 300 and 350 kg cement content and 40, 50, 75 and 100 kg pozzolan addition for 1 m^3 concrete. The efficiency of the pozzolan was obtained by using Bolomey and Feret strength equations on 28-day-old concretes. Maximum pozzolan amount with the optimum efficiency was determined. This study shows that the efficiencies obtained from each strength equations are similar and these values decrease with the increase of pozzolan/cement ratio.

Keywords: Concrete; Compressive strength; Blended cement; Pozzolan; Efficiency

1. Introduction

Pozzolans provide a way for an economic production of concrete and can improve the properties of concrete, such as durability. These properties are valid for fly ashes as well as natural pozzolans. Natural pozzolans are available at limited regions of the world. Chemical properties and the pozzolanic activities of natural pozzolans vary depending on the region of the source [1].

Efficiency can be identified as the ratio of binding of the pozzolan to binding of the cement.

Although there are investigations about efficiencies of fly ashes, there is no study with natural pozzolans in this area.

Earlier study by Smith [2] has determined the efficiency factor of fly ashes using the idea which is based on the water/cement ratio to compressive strength of concrete.

$$\left(\frac{W}{C}\right) \text{ and } \frac{W}{C'}\left[\frac{1}{1+\left(\frac{kF}{C'}\right)}\right] \tag{1}$$

are the W/C ratios of the plain and fly ash concretes, respectively.

Smith has obtained the efficiency factors of fly ashes using Eq. (2).

$$\left(\frac{W}{C}\right) = \frac{W}{C'}\left[\frac{1}{1+\left(\frac{kF}{C'}\right)}\right] \tag{2}$$

where k is the efficiency factor, C is cement content of control concrete, C' is cement content and F is the fly ash content in a concrete of equal strength.

Babu and Rao [3] have separated the efficiency factor into two parameters, including general efficiency factor and percentage efficiency factor. They used the relation between W/C ratio and compressive strength to obtain the efficiency factors. Pekmezci and Uyan [4] have also suggested using this method for determination of the efficiency factor.

Akman and Yucel have used the Bolomey equation (Eq. (3)) to determine the efficiency factors.

$$f_c = K_B\left(\frac{C}{W+v} - k'\right) \tag{3}$$

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Table 1
Properties of cement and natural pozzolan

	Cement	Natural pozzolan
Blaine specific area (cm^2/g)	3420	4350
Specific gravity (g/cm^3)	3.15	2.25
Insoluble material (%)	0.39	47.8
Ignition loss (%)	1.13	11.00
Pozzolanic activity	–	92
SiO_2 (%)	20.45	63.96
Al_2O_3 (%)	5.30	12.50
Fe_2O_3 (%)	2.65	4.00
CaO (%)	63.36	3.40
MgO (%)	2.99	2.45
K_2O (%)	0.64	–
SO_3 (%)	3.29	0.20
C_3A	9.6	–
C_3S	51.6	–
C_2S	18.1	–
7-day compressive strength (N/mm^2)	37.5	–
28-day compressive strength (N/mm^2)	48.3	–

Table 2
Physical properties and grading of the aggregates

Aggregate type	Specific gravity (kg/m^3)	Mix proportion (%)	Percentage passing						
			Sieve size (mm)						
			16	8	4	2	1	0.5	0.25
Crushed limestone	2710	50	100	73	12	2	2	1	1
Sea sand	2580	25	100	99	97	82	69	48	12
Limestone powder	2720	25	100	100	95	61	44	30	15
Mix			100	86	54	37	29	20	7

K_B, Bolomey coefficient, and k' were determined using the experimental results. Then, by using these coefficients, efficiency factors were determined by Eq. (4) [5].

$$f_c = K_B\left(\frac{C + kF}{W + v} - k'\right) \tag{4}$$

Various efficiency factors were obtained for different pozzolans at investigations. Babu et al. [6–8] has obtained these values at 28 days between 0.33 and 1.15 for fly ashes, between 0.80 and 1.29 for ground granulated blast furnace slag and between 1.11 and 6.85 for silica fume for different replacement levels.

In this study, efficiency of a natural pozzolan on the compressive strength of concrete was investigated. Fifteen concretes including control specimens with 300, 350 and 400 kg/m^3 cement dosage and pozzolan concretes designed replacing 50 kg of cement from control concretes with 40, 50, 75 and 100 kg of natural pozzolan were studied. Efficiencies were determined by the compressive strength test results, Bolomey and Feret strength equations.

2. Materials and test procedure

Properties of the ordinary Portland cement and the natural pozzolan used for the concrete production are given in Table 1. The natural pozzolan, which is a volcanic tuff obtained from Uzuntarla-Turkey, is a class N pozzolan according to ASTM C618-03 [9] standard. Physical, mechanical and chemical tests were carried out on the cement and the pozzolan. Strength activity index test was also carried out on the natural pozzolan according to ASTM C311 [10] standard. For strength activity index test, control specimens were produced with 500 g of Portland cement, 1375 g of sand and 242 g of water; specimens with pozzolan were produced with 400 g of Portland cement, 100 g of pozzolan and 1375 g of sand and water, which was required for flow of control mixture. Specimens were cast in 5-cm cube moulds. Strength activity index of the pozzolan was calculated by the ratio of strengths of test specimens to the strengths of control specimens at the end of the curing time of 28

Table 3
Mixture compositions of concretes

Concrete code	Cement (kg/m^3)	Natural pozzolan (kg/m^3)	Water (kg/m^3)	Crushed stone (kg/m^3)	Sea sand (kg/m^3)	Crushed stone sand (kg/m^3)	Slump (cm)	Calculated volume of void (%)	28-day compressive strength (N/mm^2)
C300T00	300	0	234	899	428	451	7.0	0.7	26.8
C250T40	250	40	235	893	425	448	7.0	0.9	24.8
C250T50	245	49	218	912	434	458	6.0	0.9	29.2
C250T75	244	74	228	884	421	443	7.0	1.0	25.4
C250T100	254	102	237	849	404	426	8.0	1.1	26.6
C350T00	350	0	238	872	415	438	9.0	0.7	30.9
C300T40	300	40	238	871	415	437	7.0	0.6	32.9
C300T50	300	50	237	865	412	434	7.0	0.7	33.4
C300T75	296	74	236	853	406	428	7.0	0.8	34.4
C300T100	299	99	242	828	394	416	7.5	0.8	34.0
C400T00	402	0	217	875	416	440	8.0	0.9	42.1
C350T40	350	40	234	852	406	427	7.5	0.8	40.2
C350T50	351	50	233	849	404	426	9.0	0.7	40.8
C350T75	352	75	245	806	383	404	8.5	1.1	41.8
C350T100	357	103	253	789	375	396	9.0	0.6	42.2

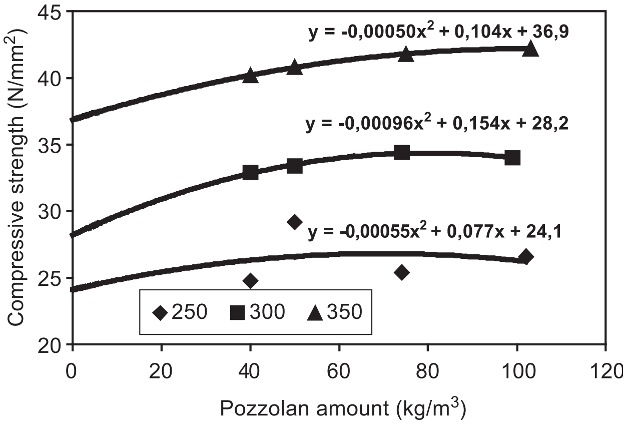

Fig. 1. Relation between pozzolan amount and compressive strength.

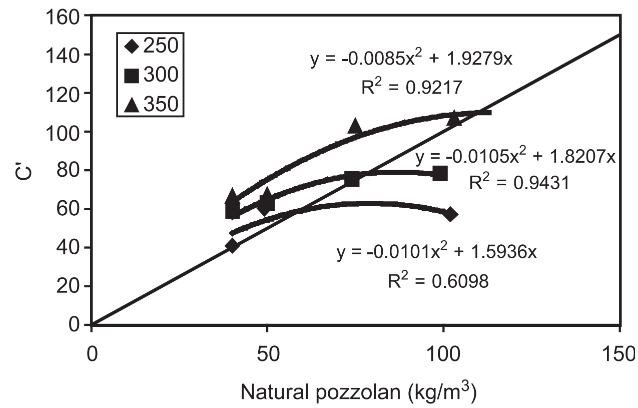

Fig. 2. Relation between equivalent cementitious material (for Bolomey equation) and natural pozzolan used.

days in water. Compressive strength test of the cement was applied according to TS 24 Turkish Standard. Water/cement/sand ratio was 1:2:6. Dimensions of the specimens were $40 \times 40 \times 160$ mm. Compressive strength tests were applied on the specimens after bending. Washed sea sand, crushed stone powder and limestone-based crushed stone having 16-mm maximum size were used as the aggregates. Specific gravity and grading of the aggregates are given in Table 2.

Concrete specimens were cured in 20 ± 2 °C lime-saturated water and compressive strength tests were carried out in 28 days. Concretes were coded with cement content + natural pozzolan amount for 1 m^3 (the number after C indicates amount of cement and the number after T indicates amount of natural pozzolan). The compositions of the concretes are given in Table 3.

3. Determination of the efficiency of the natural pozzolan providing maximum strength

Pozzolan amount–strength relations were determined for each concrete type to obtain the pozzolan amount which provides maximum strength. The trend of the pozzolan–strength curves are presented in Fig. 1. These curves keep the same character and decrease after a critical pozzolan amount at which the strength reaches a maximum value.

Abscissas of the maximum strength curves show the pozzolan amounts which provide maximum strength which were shown in Table 4.

Bolomey (Eq. (5)) and Feret (Eq. (6)) strength equations were used for determining equivalent cementitious material which would be used to obtain optimum efficiency of the natural pozzolan.

$$f_c = K_B\left(\frac{C}{W+v} - k'\right) \tag{5}$$

where K_B is the Bolomey coefficient; k' is the coefficient; f_c is the compressive strength of the concrete (N/mm^2); C is the cement content of concrete (kg/m^3); W is the water content of concrete (kg/m^3) and v is the volume of the voids (dm^3/m^3).

$$f_c = K_f\left(\frac{c}{c+w+v}\right)^2 \tag{6}$$

where K_F is the Feret coefficient; f_c is the compressive strength of the concrete (N/mm^2); c is the cement content of concrete (dm^3/m^3); w is the water content of concrete (dm^3/m^3) and v is the volume of the voids (dm^3/m^3).

K_B (Bolomey) and K_F (Feret) coefficients were determined by the material content and 28-day compressive strength of concrete. k' Value was obtained as 0.34 for the best correlation to determine the K_B value. After the

Table 4
Pozzolan amount for maximum strength

Cement dosage (kg/m^3)	250	300	350
Pozzolan amount for maximum strength (kg/m^3)	70	80	103

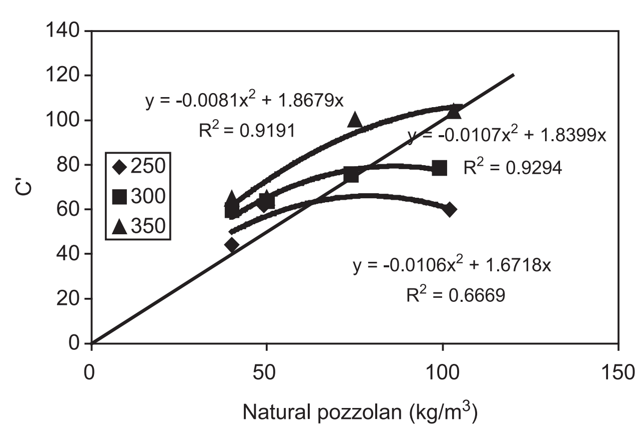

Fig. 3. Relation between equivalent cementitious material (for Feret equation) and natural pozzolan used.

Table 5
Equivalent cementitious material amount for the maximum strength

Cement (kg/m^3)	Natural pozzolan (kg/m^3)	C' (Bolomey)	C' (Feret)
250	70	62	65
300	80	78	79
350	103	108	106

determination of the coefficients, the Bolomey and Feret equations were transformed to Eqs. (7) and (8). C' and c' were determined using the material content in concretes which should be used to give the same strength with test results

$$f_c = K_B\left(\frac{C+C'}{W+h} - k'\right) \tag{7}$$

$$f_c = K_f\left(\frac{c+c'}{c+c'+w+h}\right)^2 \tag{8}$$

where C and c indicate cement content, C' and c' indicate pozzolan as equivalent cementitious material.

Relation between equivalent cementitious material and natural pozzolan content in concrete are shown in Figs. 2 and 3 for Bolomey and Feret equations. A correlation was obtained for an equation which has the form $C' = aT^2 + bT$ with a maximum point in the relation. Where, C' is equivalent cementitious material and T is natural pozzolan amount. $C' - T$ parabols have high correlations with both Bolomey and Feret equations.

Equivalent cementitious material amount (C') for the maximum strength which were calculated by the curves from Figs. 2 and 3 for either Bolomey or Feret equations are given in Table 5.

$T = C'$ line illustrates that 1 unit natural pozzolan amount is equal to 1 unit cement for cementitious property. In other words, the efficiency factor of natural pozzolans is equal to 1.

4. Discussions

From Fig. 1, it can be seen that all of the curves have a decreasing trend after a maximum point. This shows that pozzolan have a negative effect on the compressive strength when used at a high dosage. Although this decreasing tendency could be clearly seen from the experimental results for both 250 and 300 dosage concretes, it is determined for 350 dosage concrete by calculation. It could have been possible to see this behavior clearly for 350 dosage concrete if the pozzolan amount were over 100 kg.

All the curves in Figs. 2 and 3 have second degree equations having a maximum point. These points show that equivalent cementitious material decreases although pozzolan is used in higher dosages. It is understood that pozzolan cannot be used efficiently as a cementitious material and plays a fine aggregate and a filler material role.

If the curves are examined individually, it can be said that equivalent cementitious material for the same amount of pozzolan varies with the variation of cement dosages and this value increases with the increase of cement dosage.

As it is widely known, natural pozzolan transforms $Ca(OH)_2$, which is a hydration product of cement to C-S-H. When the cement content of the concrete increases, hydration products will increase; consequently, $Ca(OH)_2$ amount and C-S-H will increase. Pozzolan will be used efficiently in this case.

Decreasing of the strength curve after a maximum point may be caused by the defect effect of unhydrated pozzolan. Cross-section points of pozzolan = C' line with the curves show the points where pozzolan is equal to the equivalent cementitious material. Pozzolan shows equal cementitious properties with Portland cement on this line. The amount of pozzolan, which is equal to C', increases with the increase of cement dosage. This is also caused by $Ca(OH)_2$ amount. Pozzolan-C' curves obtained from Bolomey and Feret equations confirm each other. This shows the reliability of the approach. Pozzolan content, which provides maximum strength, consequently has an equivalent cementitious material increase with the increase of cement content. There is a pozzolan/cement ratio providing the maximum strength and this value is approximately 0.28 according to results in Table 5.

5. Conclusions

The following conclusions can be drawn from this experimental study:

- There is a maximum pozzolan amount that can be used with an optimum productivity and efficiency to achieve maximum strength.
- The optimum pozzolan/cement ratio to obtain the maximum strength is approximately 0.28. This optimization method can be used for the production of blended cements.
- Efficiency decreases with the increase of the pozzolan/cement ratio.
- When equal amount of pozzolan is used, concrete with the highest cement content has the highest efficiency of pozzolan.

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