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Alkali-activated slag mortars
Mechanical strength behaviour

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Abstract

The objective of the present work is to know the joint influence of a series of factors (specific surface of the slag, curing temperature, activator concentration, and the nature of the alkaline activator) on the development of mechanical strengths in alkaline-activated slag cement mortars. To reach this aim, a factorial experimental design was carried out (a complete $2^3 \times 3^1$ design) for every age studied (3 to 180 days). Through the variance analysis, the most significant factor on the response turned out to be the alkaline activator nature. The activator used, $Na_2SiO_3 \cdot nH_2O + NaOH$, was the factor that gave the highest mechanical strengths in all tests. The next most statistically significant factor was the activator concentration, followed by curing temperature, and, finally, the specific surface of the slag. The equations of the model describing the mechanical behaviour for flexural and compressive strengths and their relationships for each age studied were established

Keywords: Granulated blast furnace slag; Alkali-activated cement; Mechanical properties; Modeling

1. Introduction

The industrial manufacturing process of cements based on the alkaline activation of blast furnace slag (AAS) started in Ukraine between 1960 and 1964 [1]. The utilisation of these types of cements has solved an important ecological problem: the use of an industrial subproduct. The use of these cements also presents economical advantages due to the lower energy cost of their production, significantly lower than that of Portland cement. These AAS cements present some technological advantages over ordinary Portland cements. These are: the development of earlier and higher mechanical strengths, lower hydration heat, better resistance to chemical attack, better behaviour upon carbonation, higher resistance of the aggregate-matrix interface, better behaviour to freeze-thaw cycles, among others [2–4]. However, they also present some problems such as rapid setting, high shrinkage, subsequent formation of microcracks, the possibility of expansive reactions occurring because of alkali-aggregate reactions, and higher formation of salt efflorescences.

Extensive investigations have been published about the main factors affecting the development of mechanical strengths of AAS mortars and concretes [5]. These factors include slag specific surface, curing temperature, activator concentration, and alkaline activator nature. In all the studies, the influence of these factors are independently studied.

For this reason, the objective of the present work is to learn the joint influence of a series of factors (specific surface of the slag, curing temperature, activator concentration, and nature of alkaline activator) on the development of mechanical strengths of alkaline-activated slag cement mortars. Likewise, mathematical models are established, describing the mechanical behaviour of the mortars as a function of the variables considered at different ages studied.

2. Methods

2.1. Materials

The chemical composition of Spanish blast furnace slags used in this work is shown in Table 1. The mortar was prepared according to the Spanish standard UNE-80-101-88. The size of the prisms was $4 \times 4 \times 16$ cm. The aggregate/slag ratio used was 2/1 and the alkaline solution/slag ratio was 0.51 for the 450 m^2/kg slag and 0.61 for the 900 m^2/kg slag. The samples were cured at 25 and 45°C for 20 h, then they were kept at ambient temperature in a humid chamber (98%) until the testing day. Flexural and compressive mechanical strengths were measured at 3, 7, 28, 90, and 180 days.

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Table 1
Chemical composition of blast furnace slag (% wt)

Slag and specific surface	SiO_2	CaO	Al_2O_3	MgO	Fe_2O_3	SO_3	S^{-2}	P.F.	R.I.	I.B. (F_3)
E-M, 450 m^2/kg	35.5	41.45	12.15	8.34	1.01	2.47	0.92	–	0.21	1.75
E-F, 900 m^2/kg	34.72	41.05	11.87	8.24	0.44	2.43	0.83	0.10	0.29	1.76

2.2. Statistical analysis

To determine the joint effect of the four factors indicated on the mechanical strengths in mortars of alkaline-activated slag, a complete factorial experimental design ($2^3 \times 3^1$) was carried out for each age studied.

The factors considered are presented in Table 2, where $A =$ specific surface, $B =$ curing temperature, $C =$ activator concentration, and $D =$ nature of alkaline activator. The factors A, B, and C were defined with two levels: a + sign was used to indicate the highest level and a − was used for the lowest level (see Table 2). C factor was defined with three levels, with a + sign for Na_2CO_3 solution., 0 for NaOH solution, and − for $Na_2SiO_3 \cdot nH_2O$ + NaOH solution. The response variables considered for that experiment were flexural and compressive strengths at 3, 7, 28, 90, and 180 days.

To determine the analysis of variance and the mathematical equation of the model for the factorial experimental design, a STATGRAPHICS Plus computer program (version 3.1) was used.

2.3. Analysis of variance

The significance assigned to each single factor studied as well as their interactions were determined. The F-tests in the ANOVA table identify the significant factors. The ANOVA table decomposes the variability of responses into contributions due to different factors. The p values obtained with the ANOVA table determine the statistical significance of each factor and their interactions. When the p values are less than 0.05, the factors or their interactions have a statistically significant effect on the response at the 95.0% confidence level [6,7].

2.4. Equation of the model

Once the significance of the factors was known, the variability of the magnitudes observed was studied. This variability can be decomposed into additional terms; each one can be assigned to one of the factors studied and their interaction. The values of the coefficients for that response were determined by least squares method for each factor level. The confidence intervals for the means were 95.0%.

The mathematical model used is described by Eq. (1) [8]:

$$y_{ijkl} = \mu + A_i + B_j + C_k + D_l + (AB)_{ij} + (AC)_{ik} + (AD)_{jl} + (BC)_{jk} + (BD)_{il} + (CD)_{kl} + E_{ijk} \quad (1)$$

where y_{ijkl} is the value of the response estimated at i, j, k, and l factor levels; μ is the general mean of the estimated value; A_i, B_j, C_k, D_l represent the effects of the four factors considered; $(AB)_{ij}$, $(AC)_{ik}$, $(AD)_{jl}$, $(BC)_{jk}$, $(BD)_{il}$, $y(CD)_{kl}$ represent the effect of binary interactions among the four factors; and E_{ijk} represents the random errors in the measurements, considering that $\gamma_{ijk} \sim N\ (o, \Phi)$. Φ was estimated using the freedom degrees available when considering negligible the interactions higher than two.

Eq. (1) can be better described if an indicator variable for each factor is defined. Eq. (1) is then transformed into Eq. (2).

$$R = \mu + A_1 X_A + B_1 X_B + C_1 X_C + Z_{ND} + \delta_{NAB} + \delta_{NAC} + \delta_{NAD} + \delta_{NBC} + \delta_{NBD} + \delta_{NCD} + E \quad (2)$$

where A_1, B_1, and C_1 represent the coefficients associated with A, B, and C factors. They are determined by least squares means. X_A, X_B, and X_C are the variables having − and + values, according to A, B, and C factors with −1 or +1 levels, respectively. In the two-level factorial designs (factors A, B, and C, see Table 1), there is an unique parameter by factor: the effect of each factor is defined as the expected increment in the response when these factor goes from − to +. Z_{ND} represents D factor, defined by three levels. It takes different values for each level. δ_{NAB} through δ_{NCD} represent the binary interactions and they also take different values for each level.

3. Results

In Figs. 1 and 2, the values of flexural and compressive mechanical strengths are shown for the alkaline-activated slag mortars as a function of the different factors considered

Table 2
Factors considered in the process of alkaline activation

Factor	Factor definition	Factor level	
A	Specific surface of slag (m^2/kg)	450, $X_A = (-1)$	900, $X_A = (+1)$
B	Curing temperature (°C)	25, $X_B = (-1)$	45, $X_B = (+1)$
C	Activator concentration (% Na_2O with respect to the weight of slag)	3%, $X_C = (-1)$	4%, $X_C = (+1)$
D	Nature of alkaline activator	$Na_2SiO_3 \cdot nH_2O$ + NaOH, $Z_D = (-1)$	NaOH, $Z_D = (0)$; Na_2CO_3, $Z_D = (+1)$

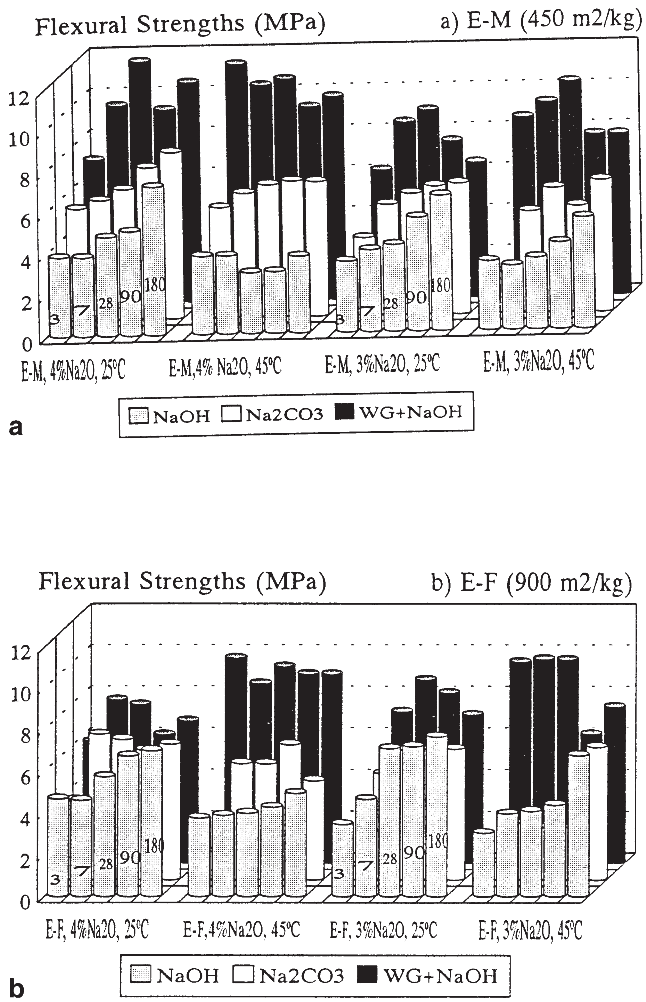

Fig. 1. Flexural strengths: (a) E-M slag, 450 m^2/kg; (b) E-F slag, 900 m^2/kg.

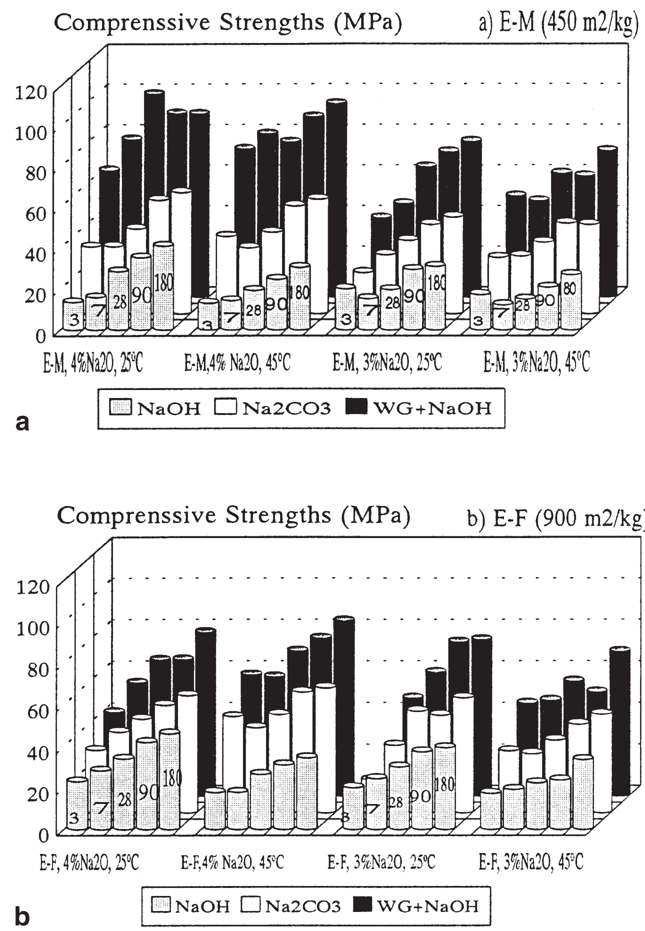

Fig. 2. Compressive strengths: (a) E-M slag, 450 m^2/kg; (b) E-F slag, 900 m^2/kg.

in the present study. It can be seen that the E-M slag (450 m^2/kg) presents mean values of strength higher than those of E-F slag (900 m^2/kg). It can also be seen that flexural and compressive strength values are higher in specimens cured at 25°C with activator concentration of 4%. With respect to the activators used, $Na_2SiO_3 \cdot nH_2O + NaOH$ mix leads in all cases to the highest strengths values, followed by Na_2CO_3 solution. NaOH solution gives the lowest strength values.

Applying the analysis of variance to the experimental results of Figs. 1 and 2, the significance of the four factors considered is obtained for each age studied. The results obtained indicate that the four factors considered do not have the same statistical significance level as can be seen from Table 3, where their *p* values also appear (obtained with a confidence interval of 95%). At all the ages studied, the most relevant factor is the alkaline activator nature flexural and compressive strengths. However, on flexural strength the relevance level of the rest of the factors depend on the age of study. For ages lower than 28 days, the order for the other factors is: activator concentration, specific surface of the slag, and curing temperature, whereas for ages greater than 28 days, the importance of curing temperature increases; the temperature is the second factor in order of significance, followed by activator concentration and slag specific surface (these two last factors are not statistically significant).

For compressive strength, the relevance of factors is constant with age. This order is: activator nature, activator concentration, and slag specific surface. The last is only significant at 3 days.

In Table 3 also appears those binary interactions statistically significant. It can be seen that reaction time plays an important role. At early ages, the main interaction on flexural strengths is curing temperature-alkaline activator. As reaction time increases, the number of important binary interactions increases. For compressive strengths, the effect is opposite at greater ages. Only one interaction is statistically important (specific surface-alkaline activator nature), while at early ages the number of binary interactions that are statistically significant is higher. In all cases, the factor of alkaline activator nature appears in all the statistically significant interactions.

The confidence levels at 95% were also determined for the values of the mean responses of the four factors studied as a function of the different levels considered for each factor. In

Table 3
Relevance order for the factors considered

Time (days)	Flexural strength (p value)[a]		Compressive strength	
	Order of factor	Signicative binary interactions	Order of factor	Signicative binary interactions
3	$D^b > C^b > A^b > B^b$ (0.0001 < 0.0077 < 0.0206 < 0.0396)	BD^b (0.0015)	$D^b > C^b > B^b > A^b$ (0.0000 < 0.0001 < 0.0008 > 0.0346)	$CD^b > AD^b > BD^b$ (0.0011 < 0.0017 < 0.0027)
7	$D^b > C^b > A > B$ (0.0000 < 0.0566 < 0.3241 < 0.7399)	BD^b (0.0332)	$D^b > C^b > B > A$ (0.0000 < 0.0016 < 0.5058 < 0.8840)	$AD^b > CD^b$ (0.0108 < 0.0134)
28	$D^b > B > C > A$ (0.0000 < 0.1446 < 0.4165 < 0.4374)	AD^b (0.0573)	$D^b > C^b > B^b > A$ (0.0000 < 0.0050 < 0.0448 < 0.9484)	AD^b (0.0166)
90	$D^b > B^b > C > A$ (0.0006 < 0.0266 < 0.1152 < 0.4750)	–	$D^b > C^b > B^b > A$ (0.0000 < 0.0020 < 0.0404 < 0.5445)	AD^b (0.0548)
180	$D^b > B^b > C = A$ (0.0004 < 0.0468 < 0.2188 = 0.2188)	$CD^b > BD^b > AC^b > AD^b$ (0.0085 < 0.0103 < 0.0181 < 0.0333)	$D^b > C^b > B^b > A$ (0.0000 < 0.0001 < 0.0298 < 0.5966)	AD^b (0.0122)

[a] Confidence level of 95%.
[b] Statistically significant.

Figs. 3 and 4 confidence levels for the flexural and compressive strengths, respectively, are represented at 28 days.

In both figures it can be seen that for *A*, *B*, and *C* factors (specific surface, curing temperature, and activator concentration, respectively) the difference among means at the different levels considered is small. This is different for *D* factor, alkaline activator nature, where there is a sharp difference between the means of −1 level, $Na_2SiO_3 \cdot nH_2O$ + NaOH, 0 NaOH, and +1 Na_2CO_3 levels.

Finally, by a least square method, the coefficients of the model were obtained as indicated before (see Eqs. 1 and 2). In Tables 4 and 5 the equations for these models are presented for both flexural and compressive strengths for each age studyied

In Table 6 the values of the coefficients of the model equations are presented. These are associated with factor *D* (Z_{ND}), alkaline activator nature. This factor takes different values for the different levels as well as flexural and compressive strengths at all ages studied. In Table 6 the values of the coefficients associated with the statistically significant binary interactions (δ_{NAB}, δ_{NAC}, through δ_{NCD}) are also presented. They are collected in the equations of the model for each age studied.

In this table is important to explain that $\delta_3{}^F{}_{BD}$ is the binary interaction for *B* and *D* factor of flexural strength at 3 days. This interaction takes a positive value when the level of the factors are −1,−1 (i.e., 25°C and 3% Na_2O in weight, respectively; see Table 2). This means that 1.89 MPa is added to the flexural strength at 3 days (see Table 4). When the levels of factors are 1,1 (i.e., 45°C and 4% Na_2O in weight, respectively), $\delta_3{}^F{}_{BD}$ takes a negative value. This means that 1.89 MPa is subtracted to the flexural strength at 3 days.

4. Discussion

The statistical analysis carried out provides knowledge of the influence of the factors considered at the levels selected on the evolution of mechanical strengths in alkaline-activated slag cement mortars. The results obtained indicate that the four factors studied present different statistical relevance. So, considering the interactions among factors in the evolution of the mechanical behaviour of the mortars, the following relevance order (− to +) can be established: slag specific surface < curing temperature < activator concentration <<< alkaline activator nature.

4.1. Slag specific surface (factor A)

The slag specific surface is the factor least statistically relevant. This factor is only significant for flexural and compressive strength at 3 days of curing. These results are similar to those indicated by some authors [9], who note that mechanical strength increment with the slag specific surface is more important at early ages.

Generally, the increase in slag specific surface favours the reactivity, but it is necessary to indicate that the mixes

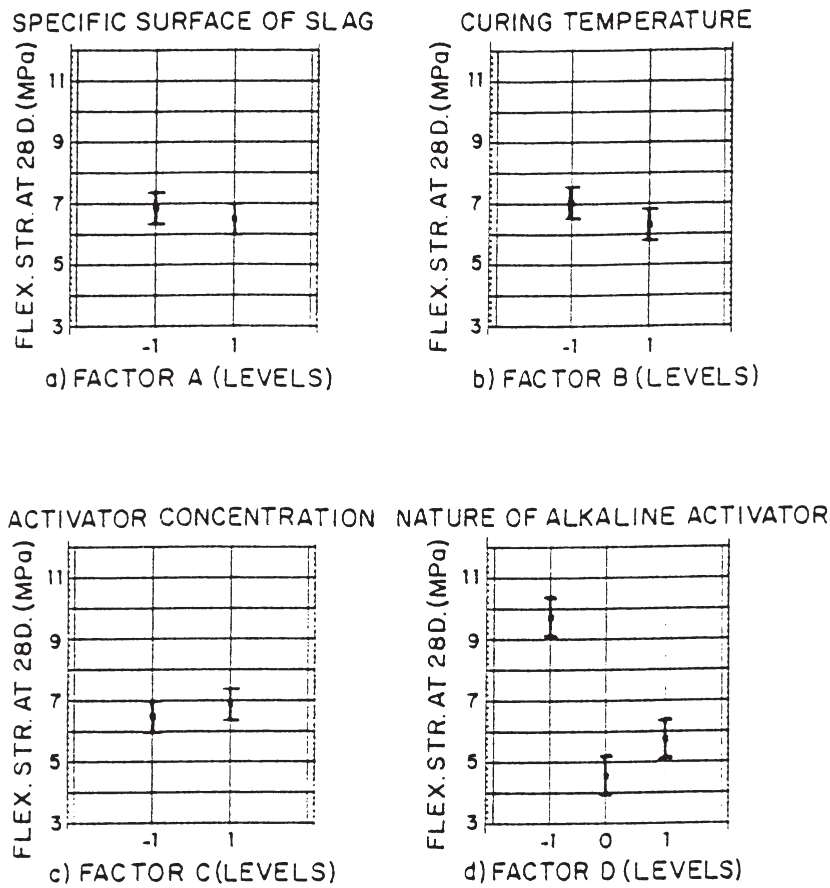

Fig. 3. Confidence intervals at 95% for the values of mean responses for flexural strengths: (a) factor *A*, slag specific surface; (b) factor *B*, curing temperature; (c) factor *C*, activator concentration; (d) factor *D*, alkaline activator nature.

with higher specific surface require higher mixing liquid content to obtain similar plasticity conditions, which produces a decrease in final strengths [3,10].

In Figs. 1 and 2 it can be seen that the variation of mechanical strengths with specific surface is highly influenced by the alkaline activator nature, indicating that this is the main binary significant interaction. When the slag is activated by NaOH and Na_2CO_3, the increase in the slag specific surface from 450 (level −1) to 900 m^2/kg, (level +1) produces an increase in mechanical strengths. Gjorv [11] indicates that the effect of the slag specific surface increment when it is activated with NaOH and Na_2CO_3 enhances the mechanical strengths; this effect is more important at early ages and low curing temperatures. However, in Figs. 1 and 2 it can be seen that when the slag is activated with $Na_2SiO_3 \cdot nH_2O$ + NaOH, mechanical strengths do not increase, but decrease with the specific surface increase.

In Figs. 3a and 4a the confidence intervals are presented for the mean responses of this factor at −1 and +1 levels at 28 days. In Fig 3a, it can be seen that flexural strength is higher for the 450 m^2/kg slag than for 900 m^2/kg one; this is confirmed by the − sign appearing in the model equations (see Table 4 where X_A is equal to −). The results obtained for compressive strengths are not clear (Fig. 4a) because sometimes a + sign is obtained and other times a − sign is obtained. In any case, because of the small (absolute) value of the coefficients, their influence is very low compared to the other three factors considered.

In this case, the influence of specific surface is conditioned by the activator type used. As was indicated earlier, the most significant factor is the activator nature: its importance can hide the effect of other factors, such as the slag specific surface.

4.2. Curing temperature (factor B)

Curing temperature is a statistically significant factor for flexural and compressive strengths. In Figs. 1 and 2 it can be seen that with variation of the curing temperature, compressive strength values are more homogeneous than those of flexural strength. The slag mortars activated with NaOH lead to a constant decrease in strength with the increase of curing temperature for all the ages studied. In mortars activated with Na_2CO_3, the increase of temperature favours the strength development at earlier ages. When activating with $Na_2SiO_3 \cdot nH_2O$ + NaOH, for compressive strength and for

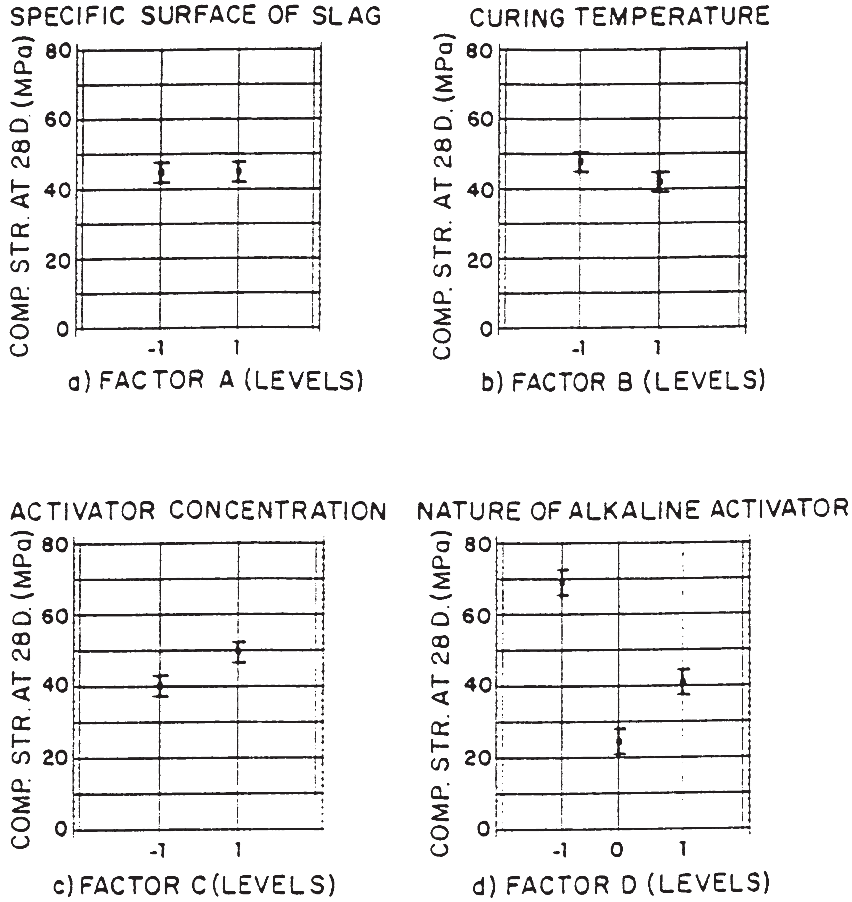

Fig. 4. Confidence intervals at 95% for the values of the mean responses for compressive strengths: (a) factor *A*, slag specific surface; (b) factor *B*, curing temperature; (c) factor *C*, activator concentration; (d) factor *D*, alkaline activator nature.

both E-M and E-F slags the same behaviour can be observed: strengths decrease as curing temperature increases. However, this effect is not so clear for flexural strengths.

From a statistical viewpoint, the influence of this factor is closely related to reaction time. At early ages (<3 days) the effect is positive, that is, mechanical strengths in mortars cured at 45°C (level, +1) are higher than those of mortars cured at 25°C (level, −1). This effect can be seen in Figs. 1 and 2 and in the + sign appearing in the equations of the model for 3 days. However, as reaction time increases, the positive effect of the curing temperature disappears, turning into a negative effect. This is shown by a − sign appearing in the equations of the model at 7, 28, 90, and 180 days (see Tables 4 and 5). It is also observed in Figs. 3b and 4b that the mean responses associated with −1 level, 25°C are higher than those associated with +1 level, 45°C. This indicates

Table 4
Mathematical equations for flexural strengths

Time (days)	Mathematical equations
3	$R_3^F = 4.68 - 0.69\,X_A + 0.59\,X_B + 0.84\,X_C + \delta_3{}^F{}_D + \delta_3{}^F{}_{BD} + \epsilon\ (\sigma \cong 1.21)$
7	$R_7^F = 6.08 - 0.16\,X_A - 0.05\,X_B + 0.33\,X_C + \delta_7{}^F{}_D + \delta_7{}^F{}_{BD} + \epsilon\ (\sigma \cong 0.75)$
28	$R_{28}^F = 6.66 - 0.18\,X_A + 0.36\,X_B + 0.19\,X_C + \delta_{28}{}^F{}_D + \delta_{28}{}^F{}_{AD} + \epsilon\ (\sigma \cong 1.10)$
90	$R_{90}^F = 6.29 - 0.15\,X_A - 0.53\,X_B + 0.35\,X_C + \delta_{90}{}^F{}_D + \epsilon\ (\sigma \cong 0.98)$
180	$R_{180}^F = 6.91 - 0.18\,X_A - 0.31\,X_B + 0.18\,X_C + \delta_{180}{}^F{}_D + \delta_{180}{}^F{}_{CD} + \delta_{180}{}^F{}_{BD} + \delta_{180}{}^F{}_{AC} + \delta_{180}{}^F{}_{AD} + \epsilon\ (\sigma \cong 0.67)$

Table 5
Mathematical equations for compressive strengths

Time (days)	Mathematical equations
3	$R_3^C = 31.70 - 2.23\,X_A + 4.41\,X_B + 5.77\,X_C + \delta_3{}^C{}_D + \delta_3{}^C{}_{CD} + \delta_3{}^C{}_{AD} + \delta_3{}^C{}_{BD} + \epsilon\ (\sigma \cong 4.39)$
7	$R_7^C = 36.17 + 0.16\,X_A - 0.74\,X_B + 4.79\,X_C + \delta_7{}^C{}_D + \delta_7{}^C{}_{AD} + \delta_7{}^C{}_{CD} + \epsilon\ (\sigma \cong 5.29)$
28	$R_{28}^C = 44.86 - 0.08\,X_A - 2.95\,X_B + 4.67\,X_C + \delta_{28}{}^C{}_D + \delta_{28}{}^C{}_{AD} + \epsilon\ (\sigma \cong 6.19)$
90	$R_{90}^C = 50.72 - 0.77\,X_A - 2.96\,X_B + 5.3\,X_C + \delta_{90}{}^C{}_D + \delta_{90}{}^C{}_{AD} + \epsilon\ (\sigma \cong 6.06)$
180	$R_{180}^C = 56.32 + 0.37\,X_A - 1.76\,X_B + 4.75\,X_C + \delta_{180}{}^C{}_D + \delta_{90}{}^C{}_{AD} + \epsilon\ (\sigma \cong 3.36)$

Table 6
δ^F and δ^C values for *D* factor (nature of alkaline activator solution)

Flexural strengths				Compressive strengths			
Levels	(−1) Na_2SiO_3 nH_2O + NaOH	(0) NaOH	(+1) Na_2CO_3	Levels	(−1) Na_2SiO_3 nH_2O + NaOH	(0) NaOH	(+1) Na_2CO_3
$\delta_3{}^F{}_D$	2.77	−1.007	−1.76	$\delta_3{}^C{}_D$	15.38	−13.82	−1.55
$\delta_7{}^F{}_D$	2.87	−2.09	−0.77	$\delta_7{}^C{}_D$	20.92	−17.63	−3.29
$\delta_{28}{}^F{}_D$	3.05	−2.12	−0.93	$\delta_{28}{}^C{}_D$	24.12	−20.33	−3.79
$\delta_{90}{}^F{}_D$	1.69	−1.24	−0.45	$\delta_{90}{}^C{}_D$	21.33	−20.08	−1.25
$\delta_{180}{}^F{}_D$	1.27	−0.76	−0.51	$\delta_{180}{}^C{}_D$	23.99	−20.87	−3.12

that mixes cured at higher temperatures (45°C) develop lower strengths than those cured at 25°C at greater ages.

These results are in accordance with those obtained by other authors [12], indicating that curing temperature increase seems to affect the development of strengths more at early ages. It has been confirmed that the curing temperature increase accelerates the slag activation process [10]. However, as reaction time increases at later ages, the curing temperature increment has a negative effect, provoking a decrease in final strength values [5]. The explanation for this phenomenon is based in the formation of a large amount of reaction product and a more heterogeneous distribution of the products at early ages in those mixes cured at higher temperature, with subsequent paste densification and a microstructural modification. So, as reaction time increases, diffusion processes are more difficult to develop and the following reactions occur slowly.

4.3. Activator concentration (factor C*)*

Activator concentration is the second statistically significant factor. In Figs. 1 and 2 it can be seen that mortars of slag activated with Na_2CO_3 or $Na_2SiO_3 \cdot nH_2O$+NaOH are affected more by the variation of activator concentration than those mortars activated with NaOH. The increase of activator concentration has a greater effect on strength development of E-M mortars than E-F mortars, except for the case of Na_2CO_3 activator. It can also be observed that the mortars activated with Na_2CO_3 are the most affected by the ratio curing temperature-activator concentration.

From the statistical point of view, this factor is significant for compressive strength at all ages studied, but it is only significant at ages earlier than 28 days for flexural strengths. In Figs. 3c and 4c it can be seen that for compressive strength the difference mean medium level is higher than for flexural strength. However, in both cases, +1 level, associated with a 4% concentration of Na_2O in weight with respect to the slag, leads to higher mechanical strengths. This is shown by a + sign associated with this factor that appears in the equations of the model.

These results are in accordance with those obtained by other authors [5]. As activator concentration increases, mechanical strengths increase within a range. Concentration values recommended are between 3 and 5% of Na_2O by slag weight. Lower values delay activation process. Higher values can originate efflorescences and brittleness problems as a function of other factors, such as slag type, activator nature, and curing temperature. Additionally, very high activator concentrations are not economically recommended.

4.4. Alkaline activator nature (factor D*)*

This is the most significant factor. In Figs. 1 and 2 it can be seen that the mortars activated with $Na_2SiO_3 \cdot nH_2O$ + NaOH give the highest strengths. The strengths are between 6 and 8 MPa for flexural strength (3 days) and between 40 and 60 MPa for compressive strength. It is also observed that for early ages (3 days), better strengths can be reached if the slag is activated with NaOH instead of with Na_2CO_3. This is explained because Na_2CO_3 solution has a lower pH, originating a lower activation rate and lower strength development at early ages. However, at later ages, strengths are lower in the case of NaOH, which is attributed to the effect of $CO_3{}^{-2}$ ions [5], leading to the formation of carbonated compounds of the type $C_3A \cdot CaCO_3 \cdot 12H_2O$ that increase the mechanical strengths.

Taking into account the effect of the other factors, it can be seen that the mortars activated with NaOH are those presenting the most homogeneous behaviour; they are the less affected by concentration variation and are less affected by undergoing a decrease of strengths because of temperature increase since early ages. Mortars activated with Na_2CO_3 and $Na_2SiO_3 \cdot nH_2O$ + NaOH lead to the highest strengths and present a higher dispersion of the results on the action of other factors. In the case of mortars activated with $Na_2SiO_3 \cdot nH_2O$ + NaOH, the strengths increase until 28 days of reaction, but at 90 and 180 days they tend to decrease slightly. This effect is sharper for flexural strength.

From the statistical viewpoint, this factor leads to greater variability in the values of the mean responses at each level and at 28 days (Figs. 3d and 4d). The slag activated with $Na_2SiO_3 \cdot nH_2O$ + NaOH is the slag that gives the highest mean mechanical strengths, followed by the slag activated with Na_2CO_3 and NaOH. The differences between these last activators are less marked than with $Na_2SiO_3 \cdot nH_2O$ + NaOH. These results indicate that the three activators used followed this order (major to minor) with respect to the mechanical strengths: $Na_2SiO_3 \cdot nH_2O + NaOH > Na_2CO_3 > NaOH$.

In Table 6 the values of the coefficients of the equations are presented. Values correspond to this factor defined by

Table 7
Binary interactions values

	(−1,−1) (1−1)	(−1,0) (1,0)	(−1,1) (1,1)		(−1,−1 (1−1)	(−1,0) (1,0)	(−1,1) (1,1)		(−1,−1) (1−1)	(−1,0) (1,0)	(−1,1) (1,1)
$\delta_3{}^F{}_{BD}$	−+ 1.89	±0.79	±1.12	$\delta_{180}{}^F{}_{AC}$	−+0.40	–	±0.40	$\delta_7{}^C{}_{AD}$	±5.95	−+3.83	−+2.14
$\delta_7{}^F{}_{BD}$	−+ 0.68	±0.25	±0.45	$\delta_{180}{}^F{}_{AD}$	±0.37	−+0.61	±0.25	$\delta_7{}^C{}_{CD}$	−+5.59	±4.16	±1.45
$\delta_{28}{}^F{}_{AD}$	± 0.63	−+0.88	±0.24	$\delta_3{}^C{}_{CD}$	−+5.65	±6.66	−+1.00	$\delta_{28}{}^C{}_{AD}$	±6.52	−+3.67	−+2.86
$\delta_{180}{}^F{}_{CD}$	−+ 0.75	±0.62	±0.13	$\delta_3{}^C{}_{AD}$	±6.71	−+4.00	−+3.01	$\delta_{90}{}^C{}_{AD}$	±4.77	−+3.67	−+1.10
$\delta_{180}{}^F{}_{BD}$	−+ 0.71	±0.63	±0.08	$\delta_3{}^C{}_{BD}$	−+4.93	±5.85	−+0.92	$\delta_{90}{}^C{}_{AD}$	±3.65	−+2.52	−+1.16

three levels: the −1 level corresponds to $Na_2SiO_3 \cdot nH_2O$ + NaOH activator, always being a positive value (the highest value at 28 days) for flexural and compressive strength. The coefficients associated with 0 and +1 levels, NaOH and Na_2CO_3, respectively, are always negative, confirming the order of importance of the activators as previously described.

4.5. Binary interactions

In Table 2 the statistically significant binary interactions are presented. In Table 7 the values of the coefficients associated with those interactions appear as a function of the level for the factor considered. The coefficients appearing in Table 7 are accompanied by ± or −+ signs, associated with the positive or negative effect of the interactions at the levels considered. These signs give information confirming some facts that are already shown, mainly related to the interactions between activator nature and slag specific surface or curing temperature.

AD interaction (specific surface-activator nature) is relevant for flexural and compressive strengths. However, specific surface factor isolated is only statistically important at 3 days. This indicates that this is a factor joint to the activator nature. The signs appearing in Table 7, as in the results of Figs. 1 and 2, indicate that the effect of specific surface increase has a negative effect when the activator is $Na_2SiO_3 \cdot nH_2O$ + NaOH, but this is not the same when NaOH or Na_2CO_3 are used.

BD interaction (curing temperature-activator nature) is more significant at early ages, which is in accordance with results exposed earlier, concerning curing temperature having greater effect on the mechanical strength development at early ages. The signs associated with the coefficients in Table 7, like the results in Figs. 1 and 2, seem to indicate that the increase in curing temperature is going to have a positive effect at early ages when the activator is $Na_2SiO_3 \cdot nH_2O$ + NaOH or Na_2CO_3, whereas the effect is negative for NaOH.

4.6. Relationships among flexural and compressive strength values

The relationships among experimental values for flexural and compressive strengths at the same age has been estimated by a simple lineal regression model. First, the statistically significant relations were estimated within a confidence level of 95% (p value < 0.05, see Table 8). Then, the equation of the simple regression model among the variables studied was estimated by minimum squares method. The lineal equations obtained are of the type of equation shown in Eq. (3), where F is the value of flexural strengths at N days and C the values for compressive strengths [see Eq. (3)]:

$$C_N = A + BF_N \tag{3}$$

The results obtained (see Table 8) indicate that a statistical significant relationship exists for all the ages studied. The p values are $<<0.05$ and good correlation coefficients are obtained. The best coefficients are obtained at 7, 28, and 90 days (0.902, 0.901, and 0.844, respectively).

5. Conclusions

From the statistical analysis of the results obtained in the present work, with the factors considered at the selected levels and applying the analysis of variance within a confidence limit of 95%, it is deduced that:

1. The equations of the models describe the mechanical behaviour of the alkaline-activated slag cement mortars at the different ages studied.
2. The mean value of mechanical strengths increases as reaction time increases.
3. The order of the most significant effects studied on the development of mechanical strengths is: nature of alkaline activator >>> activator concentration > curing temperature ≈ specific surface of slag.
4. The nature of alkaline activator is the most significant factor. As a function of the strengths obtained, the three alkaline activators used in this work maintain the following sequence: $Na_2SiO_3 \cdot nH_2O$ + NaOH >> Na_2CO_3 > NaOH.

Table 8
Lineal correlation equations among flexural and compressive strengths and their correlation coefficient

Time	Lineal equation	p value of model	Correlation coefficient
3	$C_{3d} = 10.6275 + 4.5020\ F_{3d}$	0.0000	0.775395
7	$C_{7d} = -7.12668 + 7.1167\ F_{7d}$	0.0000	0.902253
28	$C_{28d} = -3.568670 + 7.2662\ F_{28d}$	0.0000	0.901091
90	$C_{90d} = -5.90455 + 900695\ F_{90d}$	0.0000	0.844367
180	$C_{180d} = -7.63273 + 9.25291\ F_{180d}$	0.0001	0.704552

5. The behaviour of mechanical strengths for the different levels of alkaline activator (−1, 0, +1) can change with the specific surface of the slag, along with the curing temperature. The main interactions were *BD* and *AD* for the flexural strengths and *AD* and *CD* for compressive strengths.

The effect of slag specific surface increment has a positive effect when the activators used are NaOH or Na_2CO_3, whereas that effect is negative when the activator is $Na_2SiO_3 \cdot nH_2O + NaOH$. In addition, the increase of curing temperature does not favour the increase of mechanical strengths at later ages, but has a positive effect at early ages when the activator is $Na_2SiO_3 \cdot nH_2O + NaOH$ or Na_2CO_3.

Finally, from the analysis of experimental data a correlation between flexural and compressive strengths at different ages could be established. It allows the estimation of compressive strengths once the flexural strengths are known and vice versa.

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