Cement Equivalence Factor Evaluations for Fluid Catalytic Cracking Catalyst Residue

J. Payá[1], J. Monzó [1], M. V. Borrachero [1], S. Velázquez* [2]

1 Instituto de Ciencia y Tecnología del Hormigón (ICITECH)

Universidad Politécnica de Valencia

Camino de Vera s/n 46071 Valencia (Spain)

2 Escuela de Ingeniería

Universidad Panamericana Campus Guadalajara

Prolongación Calzada Circunvalación Poniente No. 49, 54010, Zapopan (México)

* Corresponding author. Tel.: +52-33-13682248; fax: +52-33-13682201.

E-mail address: svelazqu@up.edu.mx

ABSTRACT

Fluid catalytic cracking catalyst residue (FC3R) is a waste that can be used as a Portland cement replacement in pastes and mortars. The flow table results have shown that the FC3R is a water demanding addition; nevertheless it is compatible with the use of superplasticizers. The pozzolanic activity of FC3R was followed by the mechanical strength evolution with time. Pastes and mortars with FC3R incorporated have shown higher mechanical strengths than control specimens, indicating pozzolanic activity of the waste. Cement equivalence factors (*k*-factor) evaluations were carried out. The *k*-factor values for the FC3R pastes and mortars were always greater than one, indicating that to maintain the same compressive mechanical strength of the control specimen, it is enough to replace cement with a smaller amount of catalyst residue, due to its high pozzolanic activity. There is a strong agreement between the values obtained in pastes and mortars.

Keywords: Cement equivalence factor, fluid catalytic cracking catalyst residue, mechanical strength, pozzolanic activity, waste, workability.

1. Introduction

Fluid catalytic cracking catalyst residue (FC3R) is an inorganic waste material, generated in the petrol industry, specifically in the fluid catalytic cracking process. The approximate world generation of waste catalyst at the end of 1994 was of little less than a thousand tons a day [1], rising in the last decade to little more than 3000 tons per day [2-3]. Recent studies have reported the contribution to the gain of mechanical strength in mortars and concretes with Fluid catalytic cracking catalyst residue (FC3R) incorporated [2-8], and also FC3R pozzolanic activity measured in terms of lime fixation, in lime pastes as well as in cement pastes [4, 9-12]. The pozzolanic activity is largely attributed to the zeolitic structure of the catalyst residue, such as reported for other zeolites [13-14]. Antiohos et al [3] have reported FC3R cement equivalence factor values (*k*-factor), but only using a single water/binder ratio of 0.5. Those studies have confirmed the high pozzolanic activity of FC3R. The use of FC3R incorporated into hydraulic binders should be seen as an efficient use of an excellent pozzolanic material that should be optimised due its low generation volume, although the FC3R market value is worthless in these moments.

On other hand, in the present study the use of small paste specimens to evaluate the compressive mechanical strength development is introduced, comparing those results with the ones found in mortars, in order to validate this technique. If the correlationship between both specimens (pastes and mortars) would be high the usefulness of using pastes will be reflected in a gain of time in specimen preparation as well as not having to use fine aggregate, and consequently to use less material.

Therefore, the aim of this work was to determine the cement equivalence factor of FC3R, comparing the results obtained in pastes and mortars. These values have been compared to those obtained for metakaolin (MK) in the study on pastes and compared to silica fume (SF) on mortars one. It was decided to make the comparison with SF to carry out the study in mortars since this is commonly used as pozzolan for obtaining high strength composites. For pastes, it was decided to compare with MK because this is a material with similar chemical composition to FC3R, and because FC3R had positive results for whiteness, which also meets the MK and SF no. MK is a thermally activated aluminosilicate, which reacts with calcium hydroxide to produce similar gel type products as hydrated calcium silicate obtained from cement hydration, besides hydrated calcium aluminate and calcium aluminosilicate. It has been reported that substitution of cement in the range of 5-15% of MK produced significant increases in the compressive strength for high performance concretes and mortars in particularly at early ages [15, 16].

2. Experimental procedure

The spent catalyst (FC3R) was supplied by BP OIL España S.A. (Castellón, Spain). It was ground for twenty minutes, in order to obtain optimal pozzolanic activity, as has been previously reported [9]. As comparative pozzolanic materials, metakaolin (MK, from Metastar) was used in cement pastes, while densified silica fume (DSF from Ferroatlántica) was used for the mortars. Finally, the cement used was ordinary Portland cement from CEMEX (CEM I 52.5 R, Buñol, Spain). Data on the chemical composition and physical properties of the pozzolans, as well as the cement, are shown in Table 1. For tests of workability and mechanical strength in mortars, a new-generation superplasticizer was used. This was Glenium 22 from Bettor (density 1.05g/cm^3, viscosity at 20° C was 60 cps, dry residue of 20%). The mortars were prepared with siliceous aggregate, supplied by Caolines Lapiedra (Lliria, Spain) pre-mixed to obtain a fineness modulus of 3.51. Preparation of the mortars for the workability studies as well as for the mechanical strength studies was carried out according to UNE-EN 196-1:2005 standard [17]. Table 2 shows mortars mix proportions for the workability studies. The influence of superplasticizer on the performance of FC3R mortars was also carried out. To determine compressive mechanical strength on cement pastes, test specimens of 1x1x6 cm were used, based on the Köch-Steinegger method [18], as previously reported [12]. Tables 3 and 4 show mix proportions for the pastes and the mortars, in the *k*-factor study. For mortars, aggregate/binder ratio was 3/1, being binder the sum of cement and pozzolan.

3. Results and discussion

3.1 Workability studies on mortars

Control mortars and FC3R replaced mortars (15 % by weight of cement) were prepared using different water/binder ratios according to Table 2.

Figure 1 shows the results obtained on the flow table for mortars. Singular values of workability less than 110 mm were not represented, except for 0.35 water/binder ratio. The following can be observed:

- For all water/binder ratios, mortars substituted with FC3R decrease workability with regards to the control mortar. This can be explained based on the zeolitic type structure of the spent catalyst [19-20], which results in a greater water demand. Additionally a high specific surface area was found for this material (Blaine fineness 11500 cm^2/g).

- In general, the increasing percentage of superplasticizer increases the value of the workability for a given water/binder ratio.

Experimental data were adjusted to a linear model according to equation 1. Table 3 shows the results of these adjustments. Straight trend lines used to adjust experimental data satisfactorily represent the behavior of mortars with regards to % of addition of superplasticizer (note the values of the R linear correlation coefficient on Table 3).

$$\text{Workability (mm)} = \alpha \cdot \%\text{Superplasticizer} + \beta \qquad (1)$$

3.2 Studies on Mechanical Strength and the Evaluation of k-Factor in Cement Pastes

There have been previous reports on pozzolanic activity of FC3R, by means of thermogravimetric analyses and by the evaluation of mechanical strengths [2-8, 9-12]. Thus, this study is focused on determining the *k*-factor, for which it was necessary to carry out tests on different water/binder ratios, as shown in Table 4. As can be observed on this table, FC3R was compared to MK because they have similar chemical compositions. Table 5 shows the results of compressive mechanical strength on cement pastes from this study. It can be observed that in general the order of reactivity from greater to lesser is FC3R>MK>Control. For the three types of mixtures, typical behavior can be observed in regards to curing time and to water/binder ratio. That is, a gradual increase in Rc with curing time and with a decrease in the water/binder ratio. However, for both FC3R and MK, Rc values are greater than the corresponding control pastes. Only at 3 days of curing time MK paste yielded lower strength than Control paste, indicating that a slower development of pozzolanic activity of MK compared with the catalyst residue at earliest ages. For example, the mechanical strengths for the w/b = 0.40 to 7 days of curing time, the paste with 15% FC3R has a mechanical strength of 68.4. MPa, whereas 63.4 MPa was observed for the MK and 53.6 MPa for the control paste. When the curing time increases for the same w/b ratio, this reactivity order is maintained: at 90 days of curing time mechanical strength of 100.9 MPa for the FC3R paste, 93.4 MPa for the MK paste and 72.7 MPa for control paste.

For the evaluation of the contribution of a pozzolan to compressive strength, the k factor could be calculated. This k factor represents the amount of cement that can be substituted in a paste or mortar by a pozzolan to obtain the same value of mechanical strength. It can be established as [21]:

$$(w/c)_r = \frac{w}{c_x + k \cdot d_x} \tag{2}$$

where

d_x : amount of pozzolan (addition).

c_x : amount of cement.

$(w/c)_r$: water/cement ratio without addition.

w: water content to comply the same strength (Rx=Rr, being Rx the compressive strength for pozzolan/cement mixture and Rr for control mortar) requirement in both mortars (or pastes)

Thus, to isolate for the *k*-factor:

$$k = \frac{1}{(d_x/c_x)}\left[\frac{(w/c)_x}{(w/c)_r} - 1\right] \tag{3}$$

where $(w/c)_x$ corresponds to the water/cement ratio in the sample with the addition.

Based on this definition, the process to evaluate *k* is:

1. Determine the variation of compressive strength with respect to the water/cement ratio for mixtures with and without added pozzolan. It must be mentioned that for the *k*-factor study the

w/b ratio is used for the addition of pozzolan, not for the substitution (according to its definition); thus, $(w/c)_x$ must be obtained for the data from Table 3, according to

$$(w/c)_x = (w/c)_r \cdot \frac{450.0}{382.5} \tag{4}$$

2. Obtain adjustment equations correlating compressive strength R and water/cement ratio as:

$$R = R_o + \frac{h}{(w/c)} \tag{5}$$

where R_o and h are parameters from the adjustment of the equation.

3. Since the definition of *k* establishes that R_r=R_x (see fig.2), from a fixed valued for $(w/c)_r$, R_r can be calculated for a given $(w/c)_r$ value and consequently, $(w/c)_x$ could be cleared up.

4. The values of $(w/c)_r$ and $(w/c)_x$ obtained in step 3 can be used in the equation 3 for obtaining *k values*.

A physical interpretation of the k-factor is the following:

- $0 < k < 1$: implies that greater amount of pozzolan must be added with regard to the amount of cement substituted to obtain the same strength, maintaining the same water/cement ratio, and therefore reducing the water/binder ratio.
- $k = 1$: implies that pozzolan must be added in the same amount of substituted cement to equal the strength.
- $k > 1$: implies that smaller amount of pozzolan must be added with regards to substituted cement to obtain equal strength.

In Table 6 the correlation parameters of equation 5 for each curing time are shown, which has included the mean relative percentage error (e_{rm}) which has been obtained by means of the following expression:

$$e_{rm}(\%) = \frac{\sum_{i=1}^{n}\left(\frac{\left|R_{c,\exp} - R_{c,theo}\right|}{R_{c,\exp}}\right)_i}{n} 100 \tag{6}$$

- where n is the total number of pastes for each curing time. It can be seen that the adjustment achieved is very acceptable, where the average error equal to 5.3%. Table 7 shows the *k*-factor values for FC3R and MK. The following considerations can be made:
- *k*-factor for FC3R is, in general, greater than for MK for all w/b ratios and for all the curing times studied, with the exception of the 0.50 and 0.55 in 7, 28 and 90 curing days.
- For FC3R, at a fixed curing time, *k* decreases as the w/b ratio increases (coinciding with what has been reported in the literature for SF [22] and for FA [23]), whereas for MK, the behavior is the contrary. A possible explanation is that, since MK is more water demanding than the spent catalyst, when maintaining the same level of superplasticizer (optimized for the FC3R) a less workable paste would be obtained for the MK, thus yielding a better development of the mechanical strength when w/b is increased.
- The values for *k* (at a fixed w/b) for FC3R increase with curing time, reaching a maximum at 14 curing days; this indicates the time of maximum pozzolanic activity, with a slight drop for longer curing times For MK, the maximum shifts from lesser to greater curing time as the w/b ratio is decreased. Thus, for 0.55-0.50, it is at 7 days, whereas for 0.45-0.25 w/b ratio, it is at 28 days.
- The *k* values for FC3R are always greater than 1; therefore, cement can be replaced with a smaller amount of pozzolan to obtain the same strength, maintaining the same water/cement ratio.
- The *k* values for MK are also greater than 1, with the exception of those corresponding to 3 days (0.50-0.25 of w/b) and 7 days (0.25-0.30) which are smaller than 1. Thus, in those

conditions it is necessary to substitute cement for a larger amount of pozzolan to obtain the same strength.

3.3 Studies on mechanical strength and evaluation of k-factor in cement mortars

The values of compressive strength for cement mortars, manufactured according to Table 8, are tabulated in Table 9. The following considerations can be made:

- Compressive mechanical strength increases as w/b ratio decreases.
- Compressive mechanical strength increases as curing age do, from 3 to 90 days, with stabilization or slight decrease between that age and 365 days.
- For almost all w/b ratios and curing times, the mortars containing spent catalyst outperform the control ones; the latter outperform silica fume ones as well, except in the ratio w/b=0.40. The low DSF reactivity observed is attributable to the degree of densification of the material [24].

As in the study of cement pastes, the correlation parameters were also obtained for the study of mortars using equation (5). Table 10 shows the values of these parameters and the mean relative percentage error calculated with equation (6), noticing again a very acceptable fit, with the average of these errors equal to 5.9%, slightly higher than those found in the pastes study.

Given that cement pastes (specimens of 1x1x6 cm) were made under similar conditions to these mortars (the only change is the percentage of superplasticizer added), the compressive strength data obtained for mortars and pastes for the controls and for the FC3R replaced mixtures can be correlated, as it is shown in Figure 3. An acceptable relationship of the experimental data obtained by both methods can be observed. It can be seen that as the mechanical strength increases, the difference between the mortar and the paste increases. This behavior is because the mortar, which has an interface paste-aggregate, when the mechanical strength is high, it fails in the interface rather than fail in the cementitious matrix. Since the paste does not contain this interface, higher mechanical strength values are obtained in pastes. The solid line in Figure 3 is the adjustment considering an intercept equal to zero, while the dashed line in the same figure corresponds to the adjustment considering a non-zero intercept. The correlation factor is equal to 0.93 in the first case and the second case is equal to 0.95.. This adjustment follows the equation (intercept equal to zero):

$$R_{c,pastes} = 1.06 \cdot R_{c,mortars} \qquad (7)$$

The slope is practically equal to 1, showing the equivalence of both methods (when using the adjustment with non-zero intercept, the equation is modified to $R_{c,pastes} = 1.35R_{c,mortars} - 18.17$). This fact highlights the usefulness of obtaining compressive strength from pastes rather than from mortars, given the smaller amount of material used, the non-necessity of using aggregate, the shorter preparation time, an easier handling, and a less occupying volume.

In table 11 the values of *k*-factor in the mortar study are shown. The following observations can be made:

- *k*-factor for FC3R is much higher than that found for DSF at all w/b ratios and at all curing times studied.
- The behavior of *k*-factor with regards to the w/b ratio for a fixed curing time is linear (due to the type of adjustment used), and for a fixed curing time, *k* decreases as the w/b ratio increases (coinciding with reports in the literature for densified silica fume [22] and for fly ash [23]).

- *k* values (at a fixed w/b) for FC3R increase with curing time, reaching a maximum of between 14 and 28 curing days, indicating the time for maximum pozzolanic activity, while DSF shows two maximums (at 7 and 90 days) and a minimum (28 days).
- *k* values for FC3R are always greater than 1, therefore, cement could be substituted for a smaller amount of pozzolan to obtain the same strength, maintaining the same water/cement ratio.
- *k* values for DSF are all less than 1; therefore, cement would have to be substituted for a larger amount of pozzolan to obtain the same strength (negative values have no physical significance; they can simply be interpreted as an inert addition). Apparently, and according to the bibliographic data (where *k* for DSF is greater than 1), it seems that the degree of densification of the tested DSF [24], together with the high dosage of superplasticizer, may be responsible for the low *k* values in our case.

Figure 4 compares *k*-factor values obtained for mortar and cement pastes containing FC3R. In general, *k* values obtained from mortars are greater than those obtained from pastes, with the exception of those in 7 curing days (though the difference is so slight as to be considered similar). Observed differences are probably due to the different geometry used between the pastes and mortars, as well as the mathematical adjustments carried out with the linear equation model used (equation 5). Since in FC3R mortars greater cement replacement by pozzolan compared to pastes (higher k factor values) is allowed, this means that for a given curing age, we can replace more cement by FC3R in the mortar to maintain the same mechanical strength than control specimen (only cement), compared to the paste (as it has been previously explained since the latter does not contain the interface paste-aggregate). This effect is more evident when the curing time increases (generally higher k factor values in mortars than those of pastes was found) reaching a maximum at 14 days for pastes, and a maximum between 14 and 28 days for mortars, which is what evidence the curing time for maximum FC3R pozzolanic activity. This can be explained because in the paste, in the absence of aggregate, contact between the portlandite and pozzolan is favoured, facilitating the pozzolanic reaction.

4. Conclusions

From the results obtained in this study, the following conclusions can be drawn:

1. Upon studying the influence of the water/binder ratio, mortars substituted with 15% of Fluid catalytic cracking catalyst residue (FC3R) show a decrease in workability with regards to the control mortar for all the studied ratios. This behavior is attributed to the zeolitic type structure of the catalyst residue. For all percentages of addition of superplasticizer, the increase in percentage increases the workability. Straight adjustment lines of the experimental data satisfactorily represent the behavior of the mortars with regards to percentage of addition of superplasticizer.

2. With regards to the study of mechanical strength in cement mixtures, upon comparing FC3R with the control, MK and DSF, it can be concluded that with FC3R, one obtains greater compressive mechanical strength at short curing times. This is only slightly exceeded by MK at longer times, but in all cases, it is always greater than the control mixture and DSF containing mixture.

3. *k*-factor values from the study of cement pastes for FC3R are in general greater than those for MK, and always greater than 1, which implies that a smaller amount of catalyst residue would be used replacing cement to obtain the same strength. The higher k values for FC3R are

registered at 14 curing days, indicating the age of maximum pozzolanic activity, whereas the maximum pozzolanic activity for MK occurs in the range of 14-28 days of curing time.

4. Upon comparison of compressive mechanical strength data obtained with pastes and mortars, a good correlation was observed, confirming the great advantage of working with prismatic 1x1x6 cm test specimens for pastes instead of mortars.

5. The FC3R *k*-factor values obtained from mortar study are higher than 3.5 at between 14 and 28 curing days, indicating the age of maximum pozzolanic activity for FC3R.

6. Upon comparing *k*-factor values obtained with mortars and pastes, it can be noticed that, in general, they are very similar. In general, *k*-values in mortars are slightly greater. The greatest difference can be seen at 14 curing days for mixtures with low w/b ratios, as well at 28 curing days.

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Table 1 Chemical Composition and Physical Properties of Portland Cement and Pozzolans, %

Material	OPC	FC3R	DSF	MK
SiO_2	19.6	48.2	91.1	52.1
CaO	62.63	<0.01	0.48	0.07
Al_2O_3	5.3	46.0	0.2	41
Fe_2O_3	3.56	0.95	0.14	4.32
MgO	2.1	<0.01	0.19	0.19
Na_2O	0.1	0.5	-	0.26
K_2O	1.15	<0.01	0.5	0.63
SO_3	3.6	0.04	0.14	-
LOI	1.99	1.5	6.69	0.6
Relative density	3.05	2.42	2.08	2.50
Specific Surface Area (cm^2/g)	4000	11500	1200	14000
Volume Average Diameter (μ)	15.01	19.96	54.44	5.84

Table 2 Mixtures for the Workability Study

	Control	15%FC3R
Water/binder ratio (w/b)	(0.35-050)	(0.35-050)
OPC (g)	450	382.5
Water (g)	(450*(w/b))-(S*0.8)	(450*(w/b))-(S*0.8)
FC3R (g)	0	67.5
Aggregate (g)	1350	1350
Superplasticizer, S (g)	S (0-31.5)	S (0-31.5)

Table 3 Adjustment parameters for the effect of superplasticizer percentage on mortar workability according to a Linear Model (eq. 1).

w/c	Control			15%FC3R		
	α	β	R	α	β	R
0.50	38.22	122.15	0.99	39.52	112.56	0.99
0.45	9.77	120.25	0.97	7.65	121.33	0.98
0.40	7.88	105.55	0.92	5.85	104.23	0.93
0.35	1.16	101.65	0.94	0.62	100.00	0.99

Table 4 Mix Formulations for the *k*-Factor Study in Pastes

Paste	Control, FC3R, MK
Curing Temperature (° C)	20
water/binder (% Superplasticizer*)	0.25 (2.00); 0.30 (1.50); 0.35 (1.00); 0.40 (0.50); 0.45 (0.25); 0.50 (0.00); 0.55 (0.00)
Pozzolan Substitution (%)	15
Curing Time (days)	3, 7, 14, 28, 90

*% Superplasticizer is reported to binder content

Table 5 Average compressive strength of cement pastes

Paste	w/b	Curing Time (days)				
		3	7	14	28	90
		Rc (MPa)				
Control		96.35	108.24	107.80	110.01	131.53
FC3R	0.25	113.13	121.03	128.01	124.22	126.28
MK		83.69	106.25	107.03	114.84	129.54
Control		76.64	88.45	86.04	102.35	108.68
FC3R	0.30	86.08	96.58	104.52	108.37	113.46
MK		68.23	85.83	90.99	90.11	105.94
Control		64.03	71.34	75.80	85.60	87.76
FC3R	0.35	72.52	89.13	96.94	107.25	108.05
MK		58.11	80.30	81.59	93.28	91.63
Control		47.98	53.66	59.78	66.00	72.70
FC3R	0.40	49.45	68.44	71.83	75.31	100.94
MK		45.33	63.41	86.44	84.85	93.41
Control		45.73	54.29	57.72	61.45	77.91
FC3R	0.45	47.61	65.91	75.07	81.14	96.73
MK		44.15	64.23	64.19	71.64	74.43
Control		34.18	39.65	43.65	50.96	57.00
FC3R	0.50	35.87	50.18	58.60	62.03	68.91
MK		34.50	47.90	54.88	60.52	56.66
Control		26.64	31.02	39.30	47.24	51.61
FC3R	0.55	31.32	42.75	52.27	54.35	63.25
MK		29.69	44.49	49.34	58.36	61.19

Table 6 Correlation parameters of equation 5 for cement pastes study

Paste	Time (days)	R_o	h	e_{rm} (%)
Control		-29.48	31.83	3.77
FC3R	3	-37.60	43.85	4.45
MK		-19.34	30.91	4.38
Control		-33.55	36.60	4.42
FC3R	7	-34.88	51.62	8.23
MK		-6.98	33.30	3.85
Control		-17.72	31.36	2.96
FC3R	14	-19.12	46.19	5.62
MK		-6.37	36.04	5.28
Control		-9.03	30.01	4.92
FC3R	28	-10.43	41.94	6.26
MK		-4.91	38.49	6.52
Control		-17.53	37.26	3.73
FC3R	90	11.15	33.86	9.74
MK		5.52	36.18	5.08

Table 7. *k* factor values for cement pastes study as a function of curing time and water/binder ratio

Time (days)	Pozzolan	$(w/b)_r$						
		0.25	0.30	0.35	0.40	0.45	0.50	0.55
3	FC3R	1.67	1.58	1.50	1.42	1.34	1.26	1.18
	MK	0.31	0.42	0.53	0.64	0.76	0.88	1.00
7	FC3R	2.25	2.25	2.22	2.21	2.20	2.18	2.17
	MK	0.63	0.93	1.25	1.60	1.99	2.43	2.92
14	FC3R	2.59	2.57	2.55	2.53	2.52	2.50	2.48
	MK	1.49	1.64	1.79	1.95	2.11	2.29	2.47
28	FC3R	2.16	2.14	2.12	2.11	2.09	2.07	2.05
	MK	1.86	1.91	1.97	2.02	2.08	2.14	2.19
90	FC3R	2.37	2.28	2.20	2.12	2.03	1.96	1.88
	MK	0.84	1.09	1.36	1.64	1.96	2.30	2.67

Table 8 Mix Formulations for the *k*-factor study in mortars

Mortar	Control, FC3R, DSF
Curing Temperature (° C)	20
water/binder (% Superplasticizer*)	0.35 (5.00); 0.40 (3.00); 0.45 (1.00); 0.50 (0.33); 0.55 (0.00)
Pozzolan Substitution (%)	15
Curing Time (days)	3, 7, 14, 28, 90, 365

*% Superplasticizer is reported to binder content

Table 9 Average compressive strength on cement mortars study

Mortar	w/b	Curing Time (days)					
		3	7	14	28	90	365
		Rc (MPa)					
Control	0.35	52.04	64.16	62.07	68.09	78.64	81.58
FC3R		64.01	78.71	78.6	82.18	82.99	84.47
DSF		40.02	51.51	56.91	56.71	61.98	73.09
Control	0.4	47.56	61.3	56.4	61.96	72.02	71.15
FC3R		51.63	69.44	76.2	78.4	85.39	85.34
DSF		41.57	55.12	60.74	68.8	80.79	76.36
Control	0.45	47.77	50.58	56.29	63.7	64.87	59.85
FC3R		47.14	62.47	68.91	79.81	78.76	71.2
DSF		29.99	28.67	45.55	54.72	57.68	47.62
Control	0.5	40.14	43.97	49.1	53.08	55.17	50.61
FC3R		39.81	52.47	60.74	67.78	69.57	65.89
DSF		29.25	35.75	45.78	47.88	45.78	43.27
Control	0.55	29.65	38.84	43.13	45.58	50.58	45.84
FC3R		32.53	45.86	53.54	59.36	60.74	58.77
DSF		26.77	29.91	34.5	44.81	45.28	44.65

Table 10 Correlation parameters of equation 5 for cement mortars study

Mortar	Time (days)	R_o	h	e_{rm} (%)
Control	3	-0.56	19.25	7.58
FC3R		-1.91	25.2	5.33
DSF		-13.08	24.9	5.63
Control	7	-12.87	28.44	2.44
FC3R		-14.83	39.29	2.01
DSF		-27.32	37.03	13.96
Control	14	17.47	15.61	2.93
FC3R		-1.15	36.4	3.26
DSF		15.57	16.95	8.73
Control	28	28.27	13.94	6.45
FC3R		23.84	25.85	4.52
DSF		22.02	14.22	8.01
Control	90	-1.41	28.6	2.02
FC3R		-2.23	40.74	3.98
DSF		-15.77	38.88	11.44
Control	365	-2.1	27.87	4.39
FC3R		-8.34	43.43	4.25
DSF		-11.87	32.43	10.83

Table 11. *k* factor values for cement mortars study as a function of curing time and water/binder ratio

Time (days)	Pozzolan	$(w/b)_r$				
		0.35	0.40	0.45	0.50	0.55
3	FC3R	1.57	1.55	1.52	1.50	1.47
	DSF	0.30	0.15	0.00	-0.14	-0.27
7	FC3R	1.97	1.95	1.92	1.90	1.87
	DSF	0.60	0.47	0.34	0.22	0.10
14	FC3R	3.66	3.28	2.93	2.61	2.31
	DSF	0.24	0.20	0.17	0.13	0.10
28	FC3R	3.79	3.66	3.53	3.40	3.28
	DSF	-0.67	-0.76	-0.85	-0.94	-1.03
90	FC3R	2.33	2.32	2.30	2.29	2.28
	DSF	0.89	0.75	0.62	0.49	0.37
365	FC3R	2.52	2.44	2.35	2.27	2.19
	DSF	0.21	0.12	0.03	-0.06	-0.14

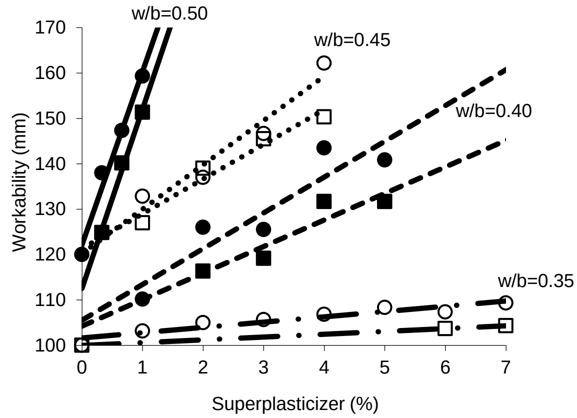
Figure Captions

Fig. 1 *Effect of water/binder ratios and superplasticizer percentage on mortars workability (Key: circle for control mortar; square for 15% FC3R mortar)*

Fig. 2. *Exemplifying the definition of the factor k*

Fig. 3. *Compressive mechanical strength correlation between pastes and mortars. Key: ○Control mortar; □ 15% FC3R mortar, solid line-adjustment with a=0, dashed line-adjustment with $a \neq 0$.*

Fig. 4. *FC3R k factor values comparison for cement pastes and mortars.*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w/b=0.45
w/b=0.40
w/b=0.35
170
160
150
140
130
120
110
100
0
1
2
3
4
5
6
7
Workability (mm)
Superplasticizer (%)

Fig. 1

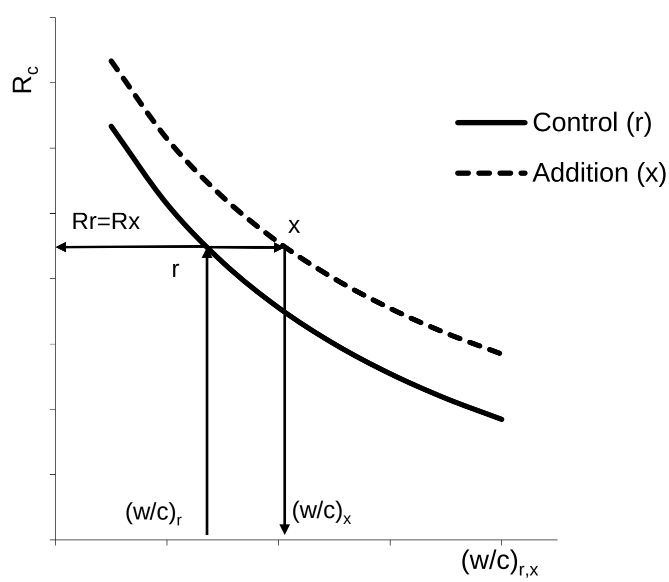
R_c
Control (r)
Addition (x)
Rr=Rx
x
r
$(w/c)_r$
$(w/c)_x$
$(w/c)_{r,x}$

Fig. 2.

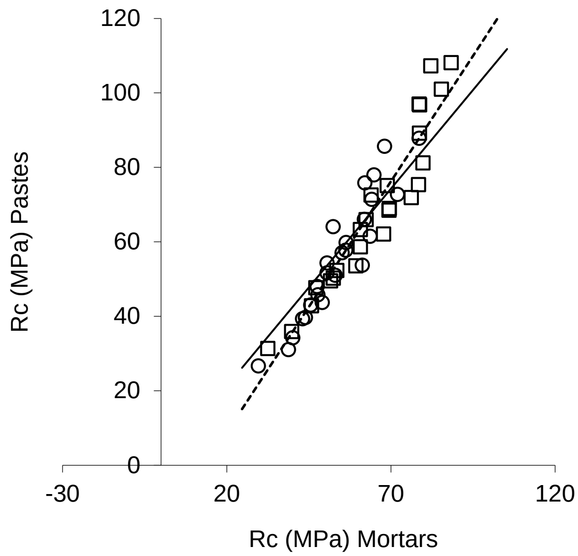
120
100
80
60
40
20
0
-30
20
70
120
Rc (MPa) Pastes
Rc (MPa) Mortars

Fig. 3.

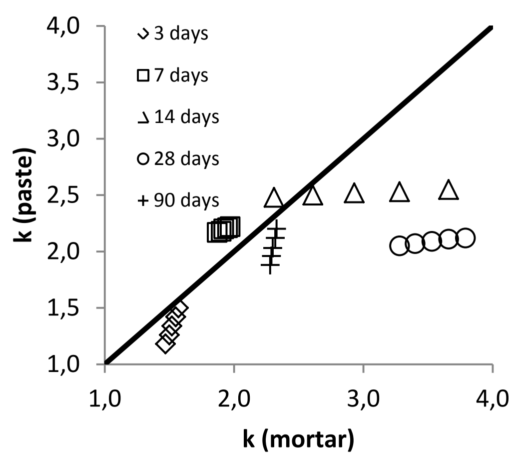
4,0
3,5
3,0
2,5
2,0
1,5
1,0
1,0
2,0
3,0
4,0
k (paste)
k (mortar)
3 days
7 days
14 days
28 days
90 days

Fig. 4.