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Feret coefficients for white self-compacting concrete

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Abstract Several tests on white mortar, micro-concrete, concrete and self-compacting concrete, considering different additions and admixtures, were conducted to characterize white cement and determine the corresponding Feret coefficients.

It was concluded that: (1) it is possible to make different mixtures of white self-compacting concrete (WSCC) with the materials adopted; (2) the method suggested by the JSCE is the one that better adapts to the studied WSCC mixtures; (3) the obtained values for the Feret coefficients can help the concrete designer predicting the compressive strength of the WSCC; (4) the Feret coefficients for WSCC are different from those for regular, white or gray, concrete.1359-5997 ©2005 RILEM. All rights reserved.

Résumé *Plusieurs testes en mortier, micro béton, béton et béton auto compactable blanc, considérant des différents additions et adjuvants, ont été conduits pour caractériser le ciment blanc et déterminer les correspondants coefficients de Feret.*

On a conclu que: (1) il est possible de produire des différents compositions de béton auto compactable blanc (WSCC) avec les matériaux adoptés; (2) la méthode suggérée para la JSCE est celle qui mieux s'adapte aux compositions de WSCC étudiées; (3) les valeurs obtenus pour les coefficients de Feret peuvent aider à prédire la résistance à la compression du WSCC; (4) les coefficients de Feret pour WSCC sont différents de ceux pour bétons, blanc ou gris, courants.

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1. Introduction

Based on the Faury method [1] and on the Feret expression [2], Lourenço [3] developed a method to predict the strength of regular concretes, i.e., gray, normal weight, normal consistency and normal strength concretes. During years, concrete mixtures, with different types of cement and different types and quantities of additions, were designed and tested to determine the corresponding Feret coefficients. This method has been used, with success, to design concrete mixtures to be applied in cast-in-place reinforced concrete structures, mainly buildings but also bridges, as well as in precast reinforced concrete elements.

White concrete has been used, in the past, basically on non-structural precast elements. Recently, some requests have been addressed, essentially to the precast industry, in order to produce white reinforced concrete elements with special architectonic requirements. Therefore, although the production of white concrete is a known process, some aspects must be taken into account in the mixture design of structural elements.

Self-compacting concrete (SCC) was first developed in Japan with the objective of achieving high durability concrete structures, independently of workmanship quality [4]. SCC presents major advantages, in relation to regular concrete, that contribute to achieve better quality concrete structures: better finish surfaces; and no need for vibration [5]. The consequent savings of manpower and equipment represent a significant economical advantage and the reduction of noise plays a key role, especially for precast industries, since it leads to better labour conditions.

White concrete, designed with SCC technology, would allow the production of precast, as well as on site, structural elements of higher quality with special aesthetic demands, fulfilling all the requirements previously mentioned. However, in order to predict the compressive strength of white self-compacting concrete (WSCC) it would be necessary to determine, first, the Feret coefficients for this new material. This has been defined, therefore, as the main objective of the study described in this article.

2. Previous studies

2.1. The feret expression

The expression of Feret relates empirically the compressive strength of a concrete with its compactness and dosage and type of cement [2]:

$$f_{c,j} = K_{1,j} \times \gamma^2 \tag{1}$$

where $f_{c,j}$ is the value of the compressive strength, in MPa, j days after the mixture; $K_{1,j}$ is the Feret coefficient, associated to the binder characteristics, j days after the mixture; and γ is the compactness of the binder paste, while fresh, given by:

$$\gamma = \frac{\nu}{\nu + I} \tag{2}$$

being ν, the absolute volume of the binder components; and I, the voids index.

Re- writing expression (1) as follows:

$$K_{1,j} = \frac{f_{c,j}}{\gamma^2} \tag{3}$$

it is possible to determine values that correlate the percentages of cement and additions, for a given binder, with the compressive strength of the concrete [6].

2.2. Feret coefficients for regular concrete

Lourenço [3, 6] tested several concrete mixtures, with different types of cement, II 32.5, I 32.5, and I 42.5, with quantities, varying from 5% to 30%, of different types of additions, fly ash and silica fume, and determined the corresponding Feret coefficients. In Table 1,

Table 1 Feret coefficients for regular gray concrete [3, 6]

Type of cement				I 42.5			
Type of addition				fly ash			
Percentage of addition	0%	5%	10%	15%	20%	25%	30%
$K_{1,7}$ (parameter assigned to the strength after 7 days)	265 to 300	240 to 260	235 to 250	225 to 245	215 to 235	205 to 225	195 to 215
$K_{1,28}$ (parameter assigned to the strength after 28 days)	315 to 350	300 to 320	290 to 310	285 to 305	275 to 295	265 to 285	255 to 275
Type of cement				I 42.5			
Type of addition				silica fume			
Percentage of addition	0%	5%	10%	15%	20%	25%	30%
$K_{1,7}$ (parameter assigned to the strength after 7 days)	265 to 300	290 to 310	285 to 300	275 to 295	265 to 285	255 to 275	245 to 265
$K_{1,28}$ (parameter assigned to the strength after 28 days)	315 to 350	340 to 360	330 to 350	320 to 340	315 to 330	305 to 325	295 to 315

Table 2 White cement BR I 42.5 and additions

Loss on ignition (P.F. %)		2.8
Insoluble residuum (R.I. %)		0.11
Density (g/m^3)		3.05
Index reflectance – Whiteness		85.11
Average particle diameter (μm)		11.4
Specific surface- Blaine (cm^2/g)		4400
Air setting times (min.):		
Initial		95
Final		165
Compressive strength (MPa)		
1		20.0
7		54.5
28		69.1
	Limestone filler	Silica fume
Loss on ignition (P.F. %)	43.1	6.0
Average Particle diameter (μm)	45	15
Density (g/m^3)	2.70	2.20
$CaCO_3$ (%)	99.0	—
SiO_2 (%)	—	98.0
Specific surface- Blaine (cm^2/g)	5150	—
Specific surface- BET (m^2/g)	—	50
Insoluble residuum in HCl (%)	0.36	—

the Feret coefficients, obtained for cement type I 42.5, are presented [3, 6].

3. Experimental program

3.1. Materials

The materials used in this investigation were a Portland cement type BR I 42.5 (Table 2); two additions—a limestone filler and a white silica fume (Table 2); three limestone crushed aggregates and two natural siliceous sands (Table 3); and a polycarboxylate type superplasticizer (Table 3).

3.2. White mortar, micro-concrete and concrete

The first tests were performed with the three mixtures presented in Table 4: a standard mortar to test cements; and a micro concrete and a concrete mixtures, both defined using the Faury method [1]. The results of the tests are presented in Table 5.

After obtaining the compressive strength for each mixture, the Feret coefficients for 1, 7 and 28 days were calculated. These results are presented in Fig. 1.

The following conclusions, related to the Feret coefficients, can be drawn:

1. $K_{1,j}$ increases with time. This is because the compressive strength increases with time for the same mixture (same γ);
2. $K_{1,7}$ and $K_{1,28}$ decrease when concrete replaces mortar. The justification for this result is based on the fact that the compressive strength depends on the relation between the mortar and the coarse aggregates. With the increase of the maximum size of the coarse aggregates, the heterogeneity of the internal stress state is also increased. Furthermore, the coarse aggregates used have low mechanical characteristics. For these reasons, when concrete replaces mortar, $K_{1,j}$ decreases;
3. $K_{1,1}$ are similar because low compressive strength values were reached, being the differences between the three mixtures not noticed.

Table 3 Aggregates and admixture

	Coarse aggreg. B2	Coarse aggreg. B1	Coarse aggreg. BA	Fine aggreg. Sand AG	Fine aggreg. Sand AF
Fineness modulus	6.89	6.07	5.20	2.57	1.07
Specific weight (kg/dm^3)	2.69	2.69	2.69	2.64	2.60
Water absorpt. (%)	0.8	0.9	1.7	0.5	1.0
Type					Polycarboxylate type superplasticizer
Density (g/m^3)					1.05 ± 0.02
Solid content (%)					18.5 ± 1.0
pH					5.0 ± 1.0
Color					Yellowish

Table 4 White mortar, micro-concrete and concrete mixtures

Constituents (kg/m^3)	Mortar	Micro-Concrete	Concrete
Cement	500	450	400
Water	250	250	186
Reference sand CEN	1500	–	–
Coarse aggregate B2	–	–	632
Coarse aggregate B1	–	–	115
Coarse aggregate BA	–	999	409
Fine aggreg. - Sand AG	–	477	499
Fine aggreg.—Sand AF	–	144	114

Table 5 Results for white mortar, micro-concrete and concrete

	Mortar	Micro Concrete	Concrete
Flow table for mortar (mm)	182	–	–
Slump—Abrams cone (mm)	–	123	115
Flow table for concrete (mm)	–	520	500
Air content (%)	4.2	3.0	2.0
Compressive strength (MPa)			
1 day	20.0	22.4	23.2
7 days	54.5	43.2	43.6
28 days	69.1	54.7	51.5

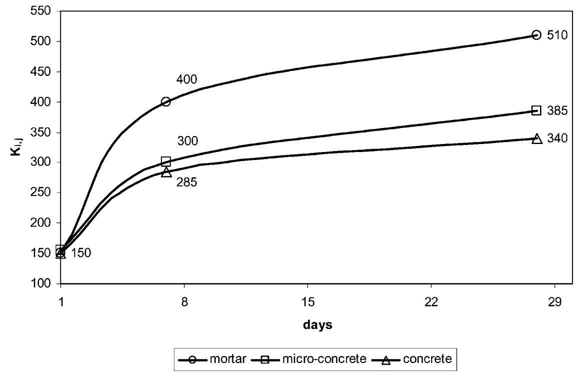

Fig. 1 Feret coefficients for white mortar, micro-concrete and concrete.

3.3. White concrete with different additions and admixtures

These tests were performed with mixtures obtained from the first concrete mixture by varying the binder, introducing two additions and an admixture. All the mixtures, shown in Table 6, were defined using the Faury method. The tests results are presented in Table 7. With the compressive strength of each mixture, the Feret coefficients were calculated for 1, 7 and 28 days and are given in Figs. 2 and 3.

Analyzing the results of the Feret coefficients, it is possible to conclude that:

1. $K_{1,j}$ increases with time;
2. $K_{1,j}$ decreases when, in a mixture where the binder is cement, 5% c.w. (in cement weight) of limestone filler is added. Again, the same happens when 20% c.w. of limestone filler is added. This result is due to the fact that this filler has no pozzolanic properties and the water-cement ratio is increased;
3. $K_{1,j}$ increases when, in a mixture where the binder is cement, 5% c.w. of silica fume is added. This result is due to the fact that this filler has pozzolanic properties;
4. $K_{1,1}$ increases when an admixture is added. The reason for this fact is that, when the admixture is used as a water reducer (since it leads to a better dispersion of the cement particles), it decreases the water/binder ratio, resulting on a higher compactness. Moreover, it also increases the velocity of the clinkers reactions with water, as a consequence of a bigger

Table 6 White concrete mixtures with and without admixtures and additions

Constituents (kg/m3)	c + 5% filler	c + 20% filler	c + 5% silica	c	c + 5% filler	c + 20% filler	c + 5% silica
Cement	400	400	400	400	400	400	400
Limestone filler	20	80	–	–	20	80	–
Silica fume	–	–	20	–	–	–	20
Admixture	–	–	–	3.6	3.6	3.6	3.6
Water	190	196	225	154	157	161	189
Coarse aggreg. B2	629	624	601	655	653	650	627
Coarse aggreg. B1	115	114	110	119	119	119	114
Coarse aggreg. BA	406	401	387	425	422	418	405
Fine aggregate -Sand AG	501	507	482	515	517	525	500
Fine aggregate -Sand AF	90	21	62	133	109	40	83

Table 7 Results for white concrete mixtures with and without admixtures and additions

	c + 5% filler	c + 20% filler	c + 5% silica	c	c + 5% filler	c + 20% filler	c + 5% silica
Slump—Abrams cone (mm)	117	122	115	128	137	143	120
Flow table for concrete (mm)	495	500	493	428	435	440	425
Air content (%)	2.0	2.0	1.9	–	–	–	–
Compressive strength (MPa)							
1 day	22.4	24.3	20.6	34.8	34.1	36.2	29.8
7 days	43.1	42.6	39.2	52.3	51.9	51.4	45.7
28 days	49.8	52.4	47.9	59.2	59.0	58.0	53.6

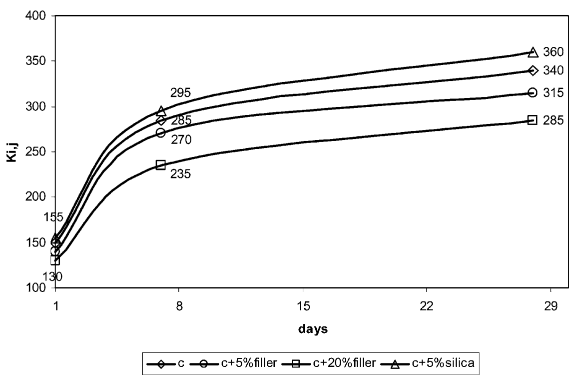

Fig. 2 Feret coefficients for white concrete without admixture.

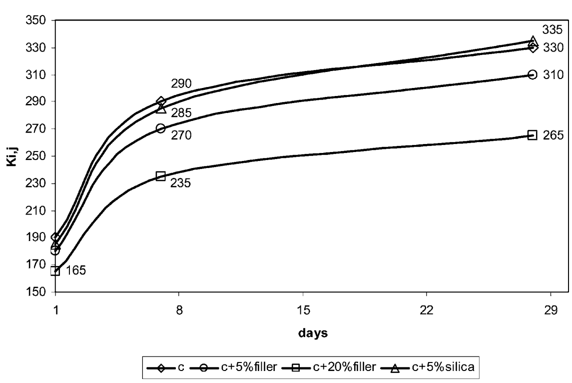

Fig. 3 Feret coefficients for white concrete with admixture.

concentration of the reagents in the mixture, resulting in a faster increase of compressive strength;

5. The Feret coefficients obtained for white concrete are similar to those determined by Lourenço [3, 6] for gray concrete.

3.4. White self-compacting concrete (WSCC)

The WSCC mixtures considered are presented in Table 8. These mixtures were defined using the methods recommended by Okamura *et al*. [4, 7, 8] and by the Japan Society for Civil Engineers [7, 9]. To test and classify the fresh concrete, namely to assess the ability to flow of the WSCC, several tests were used [10]: the slump flow test, the European L Box test, the V funnel test and the modified settlement column test.

Table 8 WSCC mixtures

Constituents (kg/m^3)	c	c + 5% filler	c + 20% filler	c + 5% silica
Cement	500	476	416	476
Limestone filler	–	24	84	–
Silica fume	–	–	–	24
Admixture	8.9	8.5	7.4	12.5
Water	155	158	161	175
Coarse aggregate B1	800	800	800	800
Coarse aggregate BA	100	100	95	76
Fine aggregate—Sand AG	400	395	390	375
Fine aggregate—Sand AF	400	395	390	375

The slump flow test evaluates the flow capacity of the SCC, by measuring the speed of the flow and the final spread (Fig. 4), under its own weight [9]. This is one of the most used tests to evaluate the consistency of a SCC. It has the advantage of providing a good assessment of the filling ability of the concrete and it can be performed in laboratory as well as on site. There is no specific worldwide assumption in relation to the reasonable value for the final spread of concrete. Several suggestions are available, based on different experiences [11–13]. The results for the four mixtures were very similar and are shown in Table 9.

With the European L-Box [14] test it is also possible to evaluate properties such as the filling ability, blocking and segregation. The test consists on filling the vertical section with concrete; lifting the gate; and allowing the concrete flow through the horizontal section (Fig. 4). The time needed for the concrete to reach

Table 9 Test results for WSCC

	c	c + 5% filler	c + 20% filler	c + 5% silica
Slump flow spread (mm)	720	700	690	710
Compressive strength (MPa)				
1 days	46.7	43.9	42.7	42.0
7 days	54.7	51.1	50.0	57.9
28 days	72.6	70.3	66.9	81.4

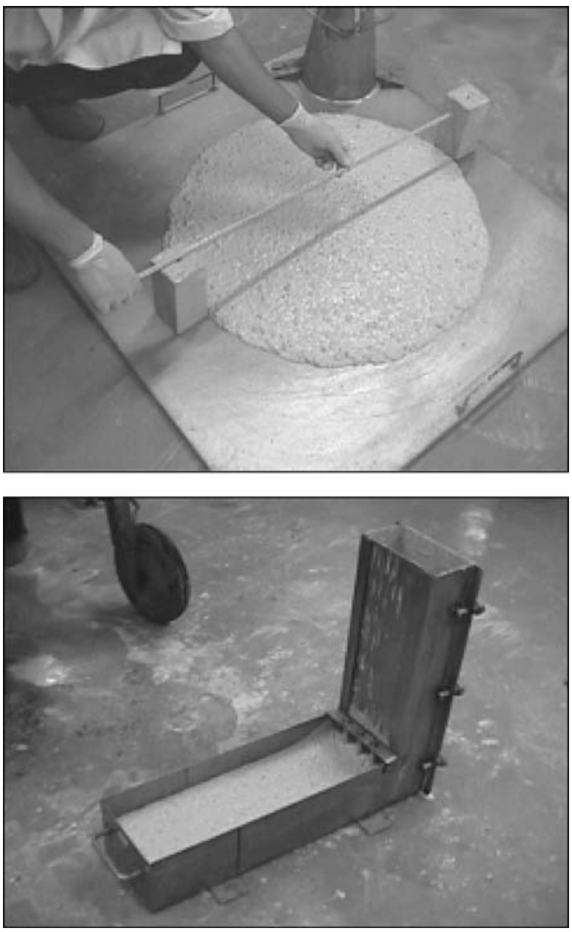

Fig. 4 Slump flow spread and European L-Box.

a distance of 200 mm, 400 mm and to stop is recorded and the height of the concrete at the end of the box (H2) and at the beginning (H1) is measured and expressed as the blocking effect = H2/H1. Values varying from 0.80 to 0.85 are suggested for the blocking effect [11]. The measured value was 0.90.

The V-funnel test [15] consists on measuring the time the concrete takes to flow through a narrow opening until a light is seen from above and through the funnel—flow time. With this test it is also possible to evaluate the resistance to segregation. Some researchers suggest for the flow time values between 4 and 10 s [14], and others values between 7 and 11 s [4]. The result for the flow time was of 10 s.

The objective of the settlement column test [15] is to quantitatively assess the capacity of a SCC to resist to segregation. The test consists on filling the column; striking the mortar table and taking samples from the top and the bottom doors. These samples must be washed out and dried before their mass is determined. The ratio between the values obtained from the top and the bottom samples is proportional to the capacity of the concrete to resist to segregation. Rooney and Bartos [15] suggested that values between 0.782 and 1.048 would be acceptable. The result for the Settlement column test was 0.95.

The compressive strength of the hardened WSCC was also determined and the results can be seen in Table 9. After obtaining the compressive strength for each mixture the Feret coefficients were calculated for 1, 7 and 28 days. These results can be observed in Fig. 5.

It is possible to take the same conclusions over the Feret coefficients for the WSCC that have been taken for the regular concrete mixtures:

1. $K_{1,j}$ increases with time;
2. $K_{1,j}$ decreases when, in a mixture where the binder is cement, 5% c.w. of limestone filler is added. Again, the same happens when 20% c.w. of limestone filler is added;
3. $K_{1,j}$ increases when, in a mixture where the binder is cement, 5% c.w. of silica fume is added; being the pozzolanic effect of the filler much more significant

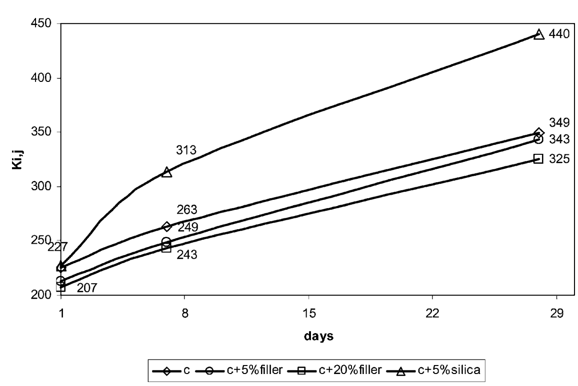

Fig. 5 Feret coefficients for WSCC.

in this case than in the case of regular white concrete, previously presented;

4. $K_{1,1}$ increases when an admixture is added; the velocity increase of the clinkers reactions with water is also much more important in this case than in the case of regular white concrete.

4. Conclusions and future developments

4.1. Conclusions

It is possible to design different mixtures of WSCC with the materials adopted.

The method suggested by the Japan Society of Civil Engineers is the one that better adapts to the studied mixtures.

The obtained values of the Feret coefficients can help concrete designers predict the compressive strength of WSCC.

The Feret coefficients for WSCC are different from those for regular, white or gray, concrete.

4.2. Future developments

It would be interesting to modify the Faury method in order to obtain better results with SCC.

Further tests should be conducted to explain the observed different influence of white silica fume on regular, white and gray, concrete and on WSCC.

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