



## Efficiency of granulated blast furnace slag replacement of cement according to the equivalent binder concept

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### ABSTRACT

The strength development of slag cement has a great consideration for the scheduling of formwork removal, prestressing operations, and other practical aspects of slag cement usage. The prediction of slag concrete strength, using the Feret's model has been studied by introducing the concept of the equivalent binder. This has led to define an efficiency coefficient of slag which distinguishes the latter with the regard to the cement. Thus, this obtained coefficient characterizes well the slag and lets to predict the slag concrete strength from strength values of a normal concrete made without slag for a given age and replacement rate. At 90 days age, the test results show that for 15% replacement rate, the slag is activated completely and gives 67% of efficiency more than the cement. For higher replacement rate, the efficiency of the slag decreases and becomes similar to that of cement for 50% replacement rate.

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### 1. Introduction

The investigation of the evolution of the strength slag cement has been seen a particular interest in the field of research, where their prediction constitutes a major concern by introducing new coefficients in the proposed models [1–4]. Currently, different types of coefficients and indexes used by the standards define the activity of the minerals admixtures replacing the cement. This led to study a new coefficient, named *efficiency coefficient*, characterizing the slag, by using the equivalent binder concept, and to compare it with those of other slags in the world [5].

Babu and Rao [6] separated the efficiency coefficient into two parameters, namely the general efficiency factor  $k_e$ , which is dependent on the age, and the percentage efficiency factor  $k_p$ , which is dependent on the replacement rate, and they proposed a polynomial inter-relationship of the efficiency coefficient depending on the replacement rate. Uyan et al. [7] determined the efficiency coefficient of slag based on the principle that mortars which have the same compressive strength, have equal water to efficient binder material ratio. They found that the efficiency coefficients of slag vary according to a logarithmic function, depending on the age and the replacement rate. Pekmezci and Akyuz [8] used the Bolognini and Feret equations to determine the equivalent cementitious material that would be used to obtain optimum efficiency of the

natural pozzolan and they found a parabolic relation between the equivalent cementitious and natural pozzolan used.

By comparing the efficiency coefficient of the mineral admixture between several properties of cement, other investigations [9] concluded that fly ash presents a higher efficiency coefficient ( $k_e = 2.5$ ) against chloride penetration as compared with the corresponding values for strength ( $k_e = 1.2$ ). In the same way, the value of the efficiency coefficient of the slag at 28 days varied from 0.7 to 1.1 for the compressive strength and from 2.1 to 2.3 for the chloride ions penetration [10]. Uji et al. [11] compared the slag efficiency coefficient between compressive strength and carbonation, and observed that for 50% of replacement, the efficiency coefficient was 0.7, 0.9 and 1.25 at 5, 10 and 28 days age, respectively, whereas, and that of carbonation was 0.68, 0.74 and 0.82. The slag is more effective in compression than in carbonation which requires long curing time.

Recently Cyr et al. [12] showed that many factors, such as the nature of cement, replacement rate, fineness, and the age of the concrete induce a great variability of the efficiency coefficient of the admixture. In the same way, Kumar et al. [13] concluded that the slag efficiency depends on slag particle size, as can be controlled through milling processes which results in variation of its surface activation. For inert admixture, a mathematical relation [4] is deduced giving the increase of compressive strength as a function of efficiency coefficient, the finesses and the replacement rate of the admixture. Thereafter the effectiveness of the slag was evaluated by separating the effect of the age, the replacement rate, the finesses and the curing temperature [2].

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This would suggest to determine the efficiency coefficient of slag by using the equivalent binder concept in Feret's model. A set of mortar and concrete specimens were prepared by several researchers [14–16] in which the cement was replaced by different amounts of slag. The results of the compressive strength have been used to identify the efficiency coefficient and express its variation according to some intrinsic parameters of the mix. The identification of the slag by its efficiency coefficient has enabled to predict the slag cement strength from ordinary cement strength.

## 2. Background information

In Algeria, the steel factory of El-Hadjar produces a large amount of slag (about 700,000 ton/year). Table 1 presents the physico-chemical characteristics of this slag [2]. This slag remains until now unrecognized product and practically not used except in very specific fields. This work examines this slag by trying to show its contribution to the development of the mechanical strengths of the cement by introducing an efficiency coefficient. The objective is to promote this slag and to analyse its activation with the cement by determining its efficiency coefficient according to a model of prediction used. This coefficient offers a fast measure to give a value to this slag and lets to predict its compressive strength using a simple model.

This work has allowed to find an efficiency coefficient by using the results of the compression strength of three tests made separately [14–16]. Bougara et al. [14] presented strength mortar re-

sults, in which the cement is substituted by 30% and 50% of slag with a W/C ratio of 0.5. Kriker [15] made a concrete with a replacement rate of 15, 30%, 40%, 45%, 50% of slag for a W/C ratio of 0.5 and 0.6. Finally Amrane and Kenai [16] studied a concrete strength with W/C ratio of 0.55 in which they substituted the cement by 15%, 30% and 50% of slag. A second set of Kriker's results [15] are reserved for checking the obtained model. All results are presented in Table 2. Other results [17,18] of compressive strength of slag concrete were used to compare their efficiency with that of Algerian slag.

## 3. Concept of the equivalent binder

A binder is the association of the cement and mineral admixture during the mix design of the concrete in which the amount of each material used depends on the objectives considered [5]. This obtained binder is often compared to the cement to illustrate the variation of the properties of the cement when it is replaced. A reference mortar was prepared with a quantity of cement  $C_0$ , and another mortar made with a mineral quantity  $pC_0$  and  $(1-p)C_0$  of cement. This mineral quantity is equivalent to a quantity  $k_e pC_0$  of cement, where  $k_e$  is a coefficient representing the activity or the efficiency due to this addition with respect to the property interest, depending on the replacement rate and age. The notion of the equivalent binder is the quantity  $(1-p)C_0 + k_e pC_0$  of cement incorporated in the mortar and it has the same consequences on the mechanical properties obtained with  $pC_0$  of mineral admixture and  $(1-p)C_0$  of cement. The values of the coefficient  $k_e$  indicate explicitly the efficiency of the mineral admixture with the respect to the cement.

For this, Feret's model was used and the amount of cement was replaced by an amount of equivalent binder to express the efficiency coefficient according to the compressive strength of cement with and without slag. Feret proposed a model of prediction of the mechanical strength of cement without mineral admixtures written as [1]:

$$S_0 = K_F \left( \frac{c}{c + w + v} \right)^2 \quad (1)$$

where  $c$ ,  $w$ , and  $v$  are the volumes of cement, water and air occluded in the mortar at the fresh state;  $K_F$  is a coefficient depending on the granular skeleton and the class of cement.

**Table 1**  
Characteristics of the slag.

Compound by mass (%)	Slag
SiO <sub>2</sub>	42.2
Al <sub>2</sub> O <sub>3</sub>	5.85
Fe <sub>2</sub> O <sub>3</sub>	1.9
CaO	42.2
MgO	4.72
Na <sub>2</sub> O	0.12
K <sub>2</sub> O	0.43
SO <sub>3</sub>	1.54
Loss on ignition	0.8
Density	2.87
Fineness cm <sup>2</sup> /g	3200–3600
Glass content %	>80

**Table 2**  
Different results of compressive strength of slag concrete [14–16].

Authors	Age (days)	Replacement rate %						Observation
		0	15	30	40	45	50	
Bougara. et al. [14] <sup>a</sup>	1	7.7		4			2.6	CEM I 32.5 Fineness (slag) = 3600 cm <sup>2</sup> /g Cure: in water, $T = 20^\circ\text{C}$ , $W/C = 0.5$
	3	15.1		9.89			6.4	
	7	22.4		17.2			14.6	
	28	30.3		35.9			29.7	
	90	34.1		42.8			39.1	
Kriker [15] <sup>a</sup>	3	20.7	16.6	15.9	14.7	9.2	7.5	CEM I 32.5 (concrete I) Fineness (slag) = 3500 cm <sup>2</sup> /g Cure: in water, $T = 20^\circ\text{C}$ , $W/C = 0.5$
	7	27.5	21.7	14.7	21.4	17.8	11.6	
	28	30.1	26	29.7	28.1	25.7	21	
	90	35.2	38.9	32.7	35.6	37.8	28.6	
Amrane et al. [16] <sup>a</sup>	3	14.5	10	8			6.5	CEM I 32.5 Fineness (slag) = 3200 cm <sup>2</sup> /g Cure: in water, $T = 20^\circ\text{C}$ , $W/C = 0.55$
	7	18.5	19.5	17.5			12	
	28	24	26	27			20.5	
	90	27	31	33			29	
Kriker 1992 [15] <sup>b</sup>	3	15	8	6.5		6.5		CEM I 32.5 (concrete II) Fineness (slag) = 3500 cm <sup>2</sup> /g Cure: in water, $T = 20^\circ\text{C}$ , $W/C = 0.6$
	7	24.5	25.5	18		16		
	28	29	34	32		24		
	90	31	37	39		33		

<sup>a</sup> Test results used for modelling the efficiency coefficient.

<sup>b</sup> Test results used for verifying of the model.

By using this equation, the volumes were replaced with their equivalent expressions and that of air was considered proportional to that of water ( $v = yw$ ). This led to the following equation:

$$S_0 = K_F \left( \frac{\frac{C_0}{\rho_c}}{\frac{C_0}{\rho_c} + \frac{W}{\rho_w} + y \frac{W}{\rho_w}} \right)^2 = K_F \left( \frac{1}{1 + \frac{W}{C_0} d_c (1 + y)} \right)^2 \quad (2)$$

where  $C_0$  and  $W$  are the weights of cement and water in the mortar,  $\rho_c$  and  $\rho_w$  are the density of the cement and water, respectively,  $d_c$  is the specific gravity of the cement ( $d_c = 3.1$ ) and  $y$  is a coefficient depending on the consistency of the concrete ( $y = 0.1$ ) for normal consistency [5].

Hence an expression  $K_F$  can be written as follows:

$$K_F = S_0 \left( 1 + \frac{W}{C_0} d_c (1 + y) \right)^2 \quad (3)$$

In the general case of a mortar containing a proportion of mineral admixture  $pC_0$ , the cement is replaced by an equivalent binder made of this mineral admixture and the cement. Therefore, the value of  $C_0$  will be substituted by the equivalent binder ( $E_b$ ) expressed as follows:

$$E_b = ((1 - p) + k_e p) C_0 \quad (4)$$

By substituting  $C_0$  in Eq. (2) with the equivalent binder expression, it will result in a new version of the Feret's model expressing compressive strength  $S(p)$  for mortar containing  $p$  slag:

$$S(p) = K_F \left( \frac{(1 - p) + k_e p}{(1 - p) + k_e p + \frac{W}{C_0} d_c (1 + y)} \right)^2 \quad (5)$$

As a result, a new expression of the efficiency coefficient can be written according to the Feret's model, as follows [1,2]:

$$k_e = 1 - \frac{1}{p} \left( 1 + \frac{\sqrt{\frac{S(p)}{K_F}} \frac{W}{C_0} d_c (1 + y)}{\sqrt{\frac{S(p)}{K_F}} - 1} \right) \quad (6)$$

#### 4. Modelling of the efficiency coefficient

The results of compressive strength  $S(p)$  given in Table 2 were selected by percentage for which the Feret's coefficient  $K_F$  was calculated from Eq. (3). Then, the efficiency coefficient was determined for each replacement rate from Eq. (6) according to the age of the concrete. The values of  $k_e$  were represented in Fig. 1.

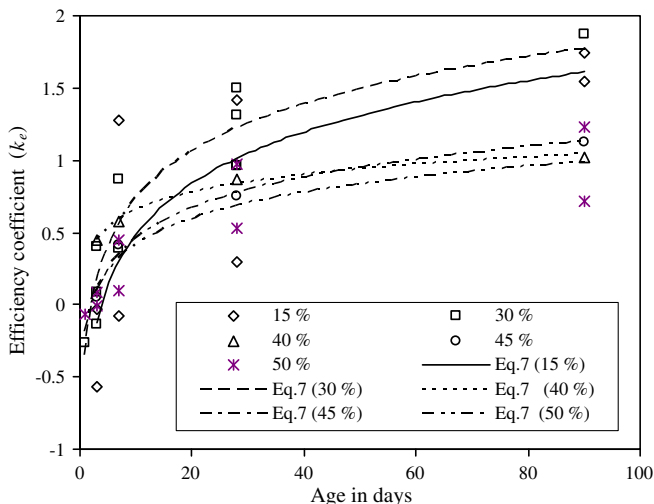


Fig. 1. Evolution of the efficiency coefficient of the slag for different replacement rate.

The large scatter of some results observed is attributed to the different data collected from several works, which reflects the variation of the efficiency of the slag for each replacement rate. Generally, it is observed that slag shows a very little efficiency at early age and acts rather like fine aggregates (filler), but at later ages its reactivity becomes effective leading to a considerable strength improvement. This obviously means that the efficiency of slag improves with age and depends on many of its characteristics. The efficiency coefficient is above 1.1 at 28 days for 30% replacement rate as shown in Fig. 1. This value is higher than those of fly ash C and F, presented by Antihos et al. [19], which were only 0.99 and 0.97, respectively.

In order to have a general model that could predict the evolution of the efficiency coefficient of this slag and later on the corresponding compressive strengths, several possible inter-relationships were checked for every replacement rate. The logarithmic function is found to be a best fit model. This finding agrees with other works [11] that have estimated the cementitious efficiency. Therefore, the efficiency coefficient of the slag is proportional to the logarithm of the time for a given mix design and can be written as the following expression:

$$k_e = A + B \ln(t) \quad (7)$$

where  $A$ ,  $B$  and  $t$  are the coefficients of the logarithmic model and the age of the specimens, respectively.

The coefficient  $A$  represents the acquired value at the age of 1 day before the real starting point of the hydraulic reaction. This coefficient increases with the replacement rate and gives a better efficiency for the large quantities of slag at early age. The  $B$  coefficient characterizes the kinetic increase of the efficiency coefficient with time; this kinetic decreases with the replacement rate. To better clarify the role of these coefficients, it is useful to represent them according to the replacement rate of the slag. This relationship is expressed by the following polynomial shapes with an acceptable coefficient of correlation  $r^2$ :

$$A = -11.34p^2 + 8.94p - 1.81 \quad (r^2 = 0.68) \quad (8)$$

$$B = 1.14p^2 - 1.56p + 0.74 \quad (r^2 = 0.7) \quad (9)$$

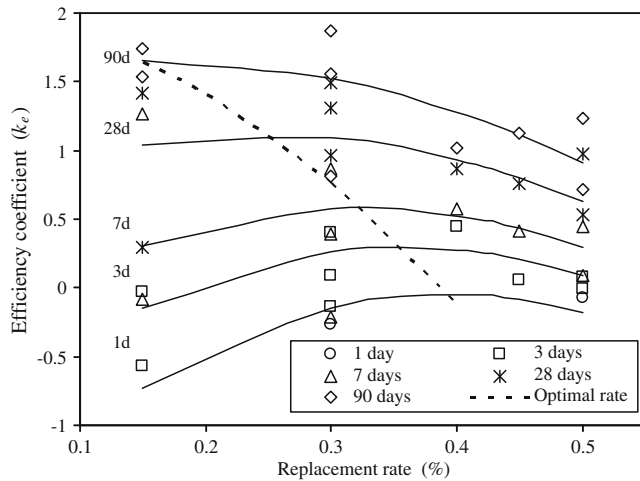
The form given to these coefficients confers a good fit for the materials used and the slag quality can be well estimated. This is in conformity with the previous works on the efficiency of mineral admixtures where it was found a parabolic variation according to the replacement rate for slag [7], natural pozzolan [8] and silica fume [20].

#### 5. Results and discussion

From the results of the efficiency coefficient  $k_e$  of the slag expressed by Eqs. (7)–(9), it is possible to calculate two characteristic ages as shown in Table 3. The first age characterizes the beginning of the activity of the slag that makes it different from the inert mineral admixture ( $k_e = 0$ ). The second age characterizes the mineral admixture when it becomes better than the cement in the development of the compressive strengths ( $k_e = 1$ ). According to the test

Table 3  
Characteristic ages of the efficiency coefficient of the slag.

Replacement rate ( $p$ )	$A$ (Eq. (8))	$B$ (Eq. (9))	Age ( $k_e = 0$ ) (days)	Age ( $k_e = 1$ ) (days)
0.15	−0.72	0.53	3.90	25.61
0.3	−0.15	0.37	1.49	21.46
0.4	−0.05	0.30	1.18	33.56
0.45	−0.08	0.27	1.36	56.24
0.5	−0.18	0.25	2.04	121.02



**Fig. 2.** Variation of the efficiency coefficient according to age and the replacement rate.

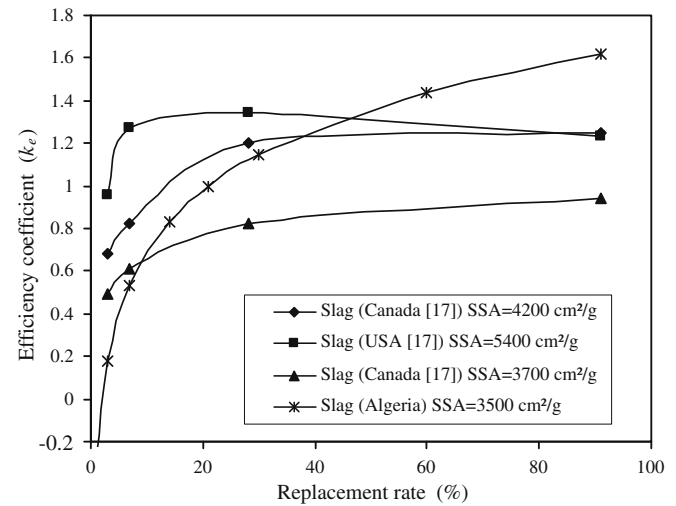
results, it is noted that the age of the beginning of the activity reaches a minimal value for the replacement rate of 37%. On the other hand, the age characterizing an activity better than that of the cement achieves a minimal value for the replacement rate of 26%. This indicates an early starting of its activation for high presence of the slag but increases only slowly. This can be explained itself by the dilution effect of a great amount of the slag at early age which offers a low efficiency. At this stage, a finer slag behaves as a filler admixture and contributes to densify the hardened paste, which improves the efficiency coefficient. In addition to that, its particles act as nucleating agents for the formation of other products and the acceleration of the hydration process [13,21]. But this does not enable to increase more the efficiency because of the delayed and limited hydraulic effect of the slag. On the other hand for low presence of slag the activity evolves quickly after its starting activity. In this case, the dilution effect is less important and the solution released by the cement hydration is rapidly saturated by lime which accelerates the slag reaction and subsequently the formation of other hydrates products [13,17,22]. When this reaction takes place, the slag cement strength is increased and the efficiency coefficient is enhanced.

To better understand this new coefficient, an optimal replacement rate of the slag has calculated by giving it a maximal activity. This has led to a representation of the calculated efficiency coefficient according to the replacement rate and the age of the concrete. The analysis of the results illustrated in Fig. 2 displays optimal replacement rates represented in Table 4 and shows a high replacement rate of 40% at early age (1 day). This optimal value of the efficiency coefficient decreases with time until 15% at later age (90 days). These results confirm that the use of high replacement rate provides a very early beginning activity. This activity does not increase sufficiently at later age. It may say that for 15%

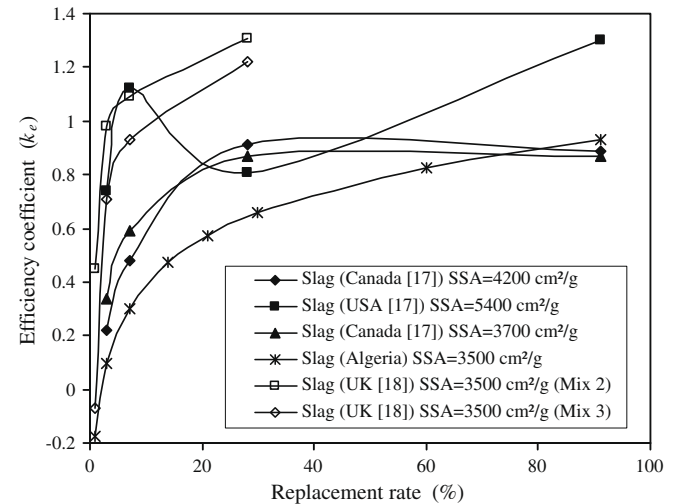
**Table 4**

Optimal replacement rate and corresponding efficiency coefficient.

Age in days	1	3	7	28	90
Optimal replacement rate (%)	39	36	32	25	15
Efficiency coefficient ( $k_e$ )	−0.05	0.29	0.58	1.12	1.67



**Fig. 3.** Evolution of the efficiency coefficients of different slag for a replacement rate of 25%. (SSA: specific surface area).



**Fig. 4.** Evolution of the efficiency coefficients of different slag for a replacement rate of 50%. (SSA: specific surface area).

**Table 5**

Comparison of the efficiency coefficients for different slag (SSA: specific surface area).

Replacement rate (%)	25				50				
Age in days	3	7	28	91	1	3	7	28	91
Slag (Canada [17]) (SSA = 4200 cm <sup>2</sup> /g)	0.68	0.82	1.20	1.25		0.22	0.48	0.91	0.89
Slag (USA [17]) (SSA = 5400 cm <sup>2</sup> /g)	0.96	1.27	1.34	1.23		0.74	1.12	0.81	1.30
Slag (Canada [17]) (SSA = 3700 cm <sup>2</sup> /g)	0.49	0.61	0.82	0.94		0.34	0.59	0.87	0.87
Slag (Algeria) (SSA = 3500 cm <sup>2</sup> /g)	0.18	0.54	1.12	1.65	−0.18	0.09	0.30	0.64	0.93
Slag (UK [18]) (SSA = 3500 cm <sup>2</sup> /g) (Mix 2)					0.45	0.98	1.09	1.31	
Slag (UK [18]) (SSA = 3500 cm <sup>2</sup> /g) (Mix 3)					−0.07	0.71	0.93	1.22	

**Table 6**

Variation of calculated and measured compressive strength of slag cement.

Age (days)	$p$	$k_e$	Strength ( $p = 0$ ) (MPa)	$K_F$ (Eq. (2))	Strength cal. (Eq. (5)) (MPa)	Strength exp. (MPa)	$\frac{S_{cal}-S_{exp}}{S_{cal}} \times 100$
3	0.15	−0.14	15	110	11.7	8	31.9
7	0.15	0.31	24.5	179	21.3	25.5	−19.8
28	0.15	1.05	29	212	29.3	34	−16.2
90	0.15	1.67	31	227	34.9	37	−6.0
3	0.3	0.26	15	110	10.8	6.5	39.8
7	0.3	0.58	24.5	179	20.6	18	12.6
28	0.3	1.10	29	212	30.1	32	−6.3
90	0.3	1.54	31	227	37.2	39	−4.8
3	0.45	0.21	15	110	8.3	6.5	21.5
7	0.45	0.44	24.5	179	16.7	16	4.3
28	0.45	0.81	29	212	25.9	24	7.3
90	0.45	1.13	31	227	33.2	33	0.6

replacement rate, the slag is activated completely and gives 67% of efficiency more than the cement. For higher replacement rate, the rest of the slag (over 15%) has relatively a low activity. The optimal replacement rate of efficiency indicates the effective contribution of this mineral admixture to the development of the compressive strengths with regard to the cement. This replacement rate is generally lower than that which gives the maximal strength.

A comparison of the efficiency coefficient of this slag with those of other slags in the world is shown in Table 5 to illustrate its effect when it replaces a part of the cement. Several previous works carried out on slag and provided from different origins were selected to examine their efficiency; the first from Canada [17], the second from USA [17] and the third from UK [18].

This comparison is the essence of the selection of two replacement rates; 25% and 50% to obtain more valid conclusion. The results illustrated in Figs. 3 and 4 show that this slag possesses an efficiency coefficient lower at early age and superior to those of other slags at later age. After about 10 days, the efficiency coefficient values of this slag compared with those of the other slags are close for the moderate replacement rate (25%). On the other hand, for high replacement rate (50%), its efficiency is low and does not reach the values of the other slags until later age (90 days). For 25% replacement rate, the efficiency coefficient of Algerian slag is above 0.18 at 3 days, whereas the other slags take values higher than 0.5. After 3 months, its efficiency exceeds 1.65 and that of the other slags ranges between 0.94 and 1.25. It is to be noted that for moderate replacement rate ( $p = 25\%$ ), the Algerian slag reaches an efficiency coefficient similar to those of other slags after 20 days and reacts as ordinary cement, while for elevated replacement rate ( $p = 50\%$ ), it requires more than 90 days.

The other results of the compressive strengths (Concrete II) [15] presented in Table 2 and not used until now, were remained for the verification of this model. Compressive strengths of the concrete made with  $p$  slag were predicted from the strength of concrete made without slag. The prediction of the compressive strengths of a slag concrete is possible by introducing an efficiency coefficient into the classical Feret's model. From the results of strength for a concrete without slag,  $K_F$  coefficient characterizing the class of the cement and aggregates can be calculated by using Eq. (3). Then, the coefficients  $A$  and  $B$  of the logarithmic model can be evaluated by using Eqs. (8) and (9) for a given replacement rate. After that, the efficiency coefficient of the slag can be deduced from Eq. (7). Thus the strength of a concrete containing ( $p$ ) proportion of slag, can be predicted by modifying the Feret's model presented in Eq. (5).

According to the obtained results, presented in Table 6, it is noted that the error of this prediction is situated between 20% and 40% at early age and 0.6–6% at later age. Regarding the effect of the replacement rate, it is clear that the error is situated between 6% and 30% for low replacement rates, 5–40% for intermedi-

ate replacement rates and 0.6–20% for high replacement rates. Therefore, this model is more reliable for high replacement rates and at later age. This can be attributed to the large scatter of the experimental results, presented by the different investigators, at early age where the slag's effect is not yet significant. In order to make this model more reliable, it is necessary for the incorporated slag to have an activity near to that of the cement.

## 6. Conclusions

The characterization of the mineral admixtures can be done by defining a new efficiency coefficient that considers the effect brought directly on a specific property of the concrete. This coefficient is determined by introducing the equivalent binder concept in Feret's model. The experimental results of three different studies were exploited to identify the slag by its efficiency coefficient which characterizes its proper contribution on the compressive strength. The modelling of this coefficient according to the age and the replacement rates gives a very clear idea of the contribution of the slag and its reactivity with the ordinary cement. Thus, it is easy to determine the age so that the efficiency will be similar to that of the cement, or other desired efficiency by varying the conditions of the mix design.

At very early ages, the efficiency coefficient of this slag is sensitive to the replacement rate but remains close to that of an inert mineral admixture. After that, its value increases with time as soon as its chemical reaction progresses. At later age, the slag's efficiency is better than that of the cement, and an optimal value is observed which decreases with time. Three weeks are required for 15% of slag to reach efficiency higher than that of the cement and more than 3 months for 50%. For low replacement rate, the efficiency develops quickly while for high replacement rate, it begins early with slow development.

Compared with other slags, the efficiency coefficient of the Algerian slag is lower at early age. At 28 days, it improves and becomes higher than those of other slags for the replacement rate of 25%. However for high replacement rate, 90 days are required to reach the same efficiency.

Furthermore, it is possible to predict the compressive strength of the slag concrete from a reference concrete made without slag. The introduction of the efficiency coefficient in the Feret's model may make the latter more relevant to the new concretes made with mineral admixture.

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