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Optimization of cement mortar strength from raw mix containing metallic particles

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Abstract

The use of metallic particles containing by-products in cement raw mix is associated with some difficulties. Apart from the technological problems associated with the sintering, it is very difficult to forecast the properties of the clinker produced. The major objective of this work is to develop an optimization procedure for the formulation of raw mix components containing metallic particles. Result showed that for raw mix containing less than 1 mass % metallic particles, the currently used formulae could be adapted and used. Calculation of the expected Fe_2O_3 content, however, should be predicted using the formula: $Fe_2O_3 = (0.0143F + 0.0111FeO + Fe_2O_{3initial})(1.3 - 1.4)$. Regression equation developed for determining the compressive strength for raw mix containing less than 1 mass % metallic particles showed a high degree of accuracy when compared with experimental values. For raw mix containing more than 2 mass %, the expected Fe_2O_3 content could be predicted using the formula: $Fe_2O_3 = (1.43F + 1.11FeO + Fe_2O_{3initial})(1.3 - 1.4)$. However, determination of the compressive strength via the proposed equations showed much discrepancy. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Cement manufacture; Metallic particles; Compressive strength; Modeling; Optimization

1. Introduction

The quality of cement clinker and consequently that of the cement produced can be prognosed using the following characteristics: chemical composition of the individual oxides; the modules' values and the microstructure, size and configuration of the clinker minerals. The first two characteristics are widely used in the preparatory stage of prognosing the burnability of raw mix and the expected chemical and mineral composition of the clinker to be produced. The morphology of the clinker minerals not only depends on the quantity and chemical composition of the liquid phase [1], but also on the homogeneity and fineness of raw mix grains [2].

Consequently, a combination of technological factors and the morphology of the raw mix components determine the quality of clinker produced. Prediction of cement quality can therefore be performed based on the analysis of the physical state and chemical composition of raw mix components, prevailing technological condition during preparation of raw mix, sintering and cooling. In the traditional raw mix, all the components exist in the oxide form and the physical state (hardness) is dependent on the genealogy. Continuous depletion of available traditional deposits had necessitated the use of industrial by-products — slag, fly ash, abrasive slurry, tyres, etc., as cement raw mix components [3,4]. Unlike raw materials of natural origin, some industrial by-products, the likes of metallurgy slag and abrasive slurry, a by-product of the machine building industry, contain metallic particles.

Analyses of the effect of metallic particles on the kinetics of cement production [5], microstructure [6] and hydration of cement paste [7] had shown that optimization of raw mix containing such by-products cannot be performed using known methods [8–10] without modifications. The major objective of this article is to develop a characteristic model for formulating raw mix component containing metallic particle and its oxide.

2. Experiment

The raw materials used for the experiments were limestone, sand, abrasive slurry and open-hearth slag. The compositions of the raw materials are presented in Table 1. The granulometric composition of abrasive slurry in mass

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Table 1
Chemical composition of raw materials

Material	Oxides content (mass %)								
	SiO_2	Al_2O_3	Fe_2O_3	FeO	Fe	CaO	Cr_2O_3	MnO	LOI
Limestone	7.66	1.19	0.62			49.50			39.95
Sand	76.71	6.60	2.81			6.64			5.61
Open-hearth slag	37.17	11.05	14.56			20.72	3.57	9.32	
Abrasive slurry	3.02	27.00	4.34	6.72	54	0.84	1.82	0.66	
1400°C[a]	1.10	22.54	74.24		1.10				
Abrasive slurry burnt at 500°C	1.32	16.42	60.52	9.5	10.3			1.31	

LOI: loss on ignition.
[a] Expected chemical composition of abrasive slurry burnt at 1400°C.

% is: 0–0.12 mm, 48–80, 0.2–1 mm 20–29 and above 1 mm, the remainder. Part of the abrasive slurry was burnt at 500°C and the chemical composition was also determined. The Fe, FeO and Fe_2O_3 contents were determined as in Ref. [11]. Quantitative analyses of Fe, FeO and Fe_2O_3 in the abrasive slurry were determined using the methodologies that prevent oxidation of Fe and FeO. The determination of Fe_2O_3 in clinker allows for the oxidation of FeO.

Using the simplex–lattice diagram Composition–Properties [12], the compositions of the raw mixes were determined (Tables 2 and 3). The dried raw materials mixed in the required proportion were ground in a ceramic-lined ball mill to a fineness of 6 to 8 mass % residue on an 80-μm size mesh. They were then watered and manually granulated. Their granules were dried and burnt in an electric furnace using silicon-heating elements. The burning temperature was gradually raised to 1400°C, with a retention time of 30 min at the maximum temperature. The entire mass of the produced clinkers is ground to a surface area of 3200 cm^2/kg. The mechanical strength of the clinkers, determined in accordance with British standard (vibrated mortar) are presented in Tables 2 and 3. The optimization parameters were 7, 28 and 180 days compressive strength. All the samples were chemically analyzed and the results are presented in Tables 6 and 9. The calculated chemical compositions of the raw mixes are presented in Tables 4 and 7.

3. Results and discussion

Analyses of the simplex–lattice diagrams taking maximum compressive strength as the optimization criteria are presented in [10]. The derived regression equation [10] approximating the relation between the components, at sand content = 9 mass % for clinker contained in Table 2 is:

$$
\begin{aligned}
y_{28} = {} & 40.12X_1 + 33.73X_2 + 34.54X_3 + 13.54X_1X_2 \\
& +30.08X_1X_3 + 33.61X_2X_3 \pm 188.97X_1X_2X_3 \\
& \pm 62.48X_1X_2(X_1 - X_2) + 6.41X_1X_3(X_1 - X_3) \\
& \pm 87.52X_2X_3(X_2 - X_3).
\end{aligned}
$$

$$
\begin{aligned}
y_{180} = {} & 52.5X_1 + 46.7X_2 + 52.5X_3 \pm 1.68X_1X_3 + 19.55X_1X_3 \\
& +26.43X_2X_3 \pm 172.41X_1X_2X_3 + 56.81X_1X_2(X_1 - X_2) \\
& +41.78X_1X_3(X_1 - X_3) \pm 73.19X_2X_3(X_2 - X_3).
\end{aligned}
$$

Table 2
Composition of raw mix and compressive strength of cement

N	Composition of raw mix (mass %)				Compressive strength (MPa)			Prognosed compressive strength (MPa)	
	Limestone (RX1)	Open-hearth slag (RX2)	Abrasive slurry (RX3)	Sand (RX4)	After 7 days	After 28 days	After 180 days	y28	y180
1	82.00	5.00	4.00	9.00	37.0	40.1	52.5	42.69	55.17
2	79.00	7.00	5.00	9.00	25.0	37.7	46.7	45.50	58.36
3	80.00	8.00	3.00	9.00	28.5	34.5	52.5	43.89	55.78
4	80.33	6.34	4.33	9.00	26.5	36.4	46.0	43.61	55.98
5	79.67	6.66	4.67	9.00	34.0	43.5	52.5	43.92	56.32
6	79.25	7.30	4.40	9.00	19.0	35.0	49.1	44.19	56.47
7	79.53	7.80	3.67	9.00	34.0	48.2	61.9	44.09	56.14
8	81.03	6.67	3.30	9.00	40.0	34.4	59.9	43.34	55.45
9	79.73	7.60	3.67	9.00	32.0	42.6	53.7	43.99	56.07
10	80.03	6.67	4.30	9.00	23.0	37.7	49.1	43.79	56.11

y28 and y180 were calculated using expected $Fe_2O_{3C} = 1.43F + 1.11FeO + Fe_2O_3$.

Table 3
Composition of cement raw mix and compressive strength

	Composition of raw mix (mass %)				Compressive strength (MPa)		Prognosed compressive strength (MPa)
N	Limestone (RX1)	Open-hearth slag (RX2)	Abrasive slurry burnt at 500°C (RX3)	Sand (RX4)	After 7 days	After 28 days	y28
1	82.00	7.00	2.00	9.00	33.6	52.5	52.84
2	80.00	8.00	3.00	9.00	32.5	57.5	52.89
3	81.00	5.00	4.00	9.00	34.0	50.2	50.56
4	81.66	5.68	2.66	9.00	38.0	56.2	51.41
5	81.34	6.33	3.33	9.00	37.5	53.7	52.02
6	80.68	6.66	3.66	9.00	39.1	54.8	51.99
7	80.33	7.33	3.33	9.00	41.2	56.3	
8	80.66	7.68	2.66	9.00	35.0	55.3	
9	81.33	7.33	2.33	9.00	36.0	52.5	
10	81.00	7.00	3.00	9.00	41.7	63.5	

The regression equation approximating the physio-mechanical strength of clinker presented in Table 3 is:

$$\begin{aligned} y_{28} = & 52.5X_1 + 57.5X_2 + 50.2X_3 + 0.11X_2 + 11.47X_1X_2 \\ & + 7.44X_2X_3 + 216.27X_1X_2X_3 + 27.78X_1X_2(X_1 - X_2) \\ & + 13.72X_1X_3(X_1 - X_3) \pm 25.80X_2X_3(X_2 - X_3). \end{aligned}$$

From the above, it is clear that the simplex-composition technique is effective as an optimization tool for a defined composition of raw mix. It cannot therefore be used to derive a representative equation for all raw mix compositions. The calculated chemical composition of the raw mixes (Table 2) using results of chemical analysis (Table 1) is presented in Table 4. It shows the chemical composition of the raw mixes, but not the expected chemical composition of the clinker produced.

During heating in air, the weight of metallic particles is expected to increase by 1.8–2.1 times depending on the extent of oxidation [11]. From the reaction stoichiometry, the increase in weight of FeO after oxidation to Fe_2O_3 and Fe to Fe_2O_3 are 1.11 and 1.43, respectively. Using the above stoichiometric coefficients, the composition of the raw mixes were computed assuming that the Fe and FeO present are converted to Fe_2O_3. The expected chemical composition of the clinkers and its compressive strength are presented in Table 5. Analysis of Tables 5 and 6 showed that the Fe_2O_{3E} content in the clinker produced far exceeded the expected amount of Fe_2O_{3C}. The extent of disparity of Fe_2O_{3D} between the calculated and the experimentally obtained values varies considerably and could be as high as 30% (Table 6).

In Table 3 is presented the composition of raw mixes containing burnt abrasive slurry. The calculated chemical composition of raw mix is in Table 7 and the analysis of the expected clinker to be produced is in Table 8. The obtained experimental values are presented in Table 9.

Analyses of Tables 7–9 showed that the Fe_2O_3 contents in Tables 7 and 8 are the same except for experimental errors. At reduced Fe and FeO content in the raw mix, their contribution to the final Fe_2O_3 value in clinker is considerably eliminated. From the above analysis, the

Table 4
Calculated chemical composition of raw mix

	Oxides content (mass %)								
N	CaO	Fe_2O_3	Al_2O_3	SiO_2	Fe	FeO	Cr_2O_3	MnO	Total
1	64.56	2.54	4.89	23.16	3.30	0.41	0.38	0.75	99.99
2	61.85	4.67	3.79	23.58	4.07	0.50	0.51	1.03	100.00
3	63.47	3.10	4.91	24.08	2.45	0.30	0.52	1.16	99.99
4	63.21	2.82	5.18	23.25	3.54	0.44	0.46	0.94	99.84
5	62.45	2.89	5.34	23.54	3.80	0.47	0.49	0.98	99.96
6	62.22	3.11	5.29	23.78	3.57	0.44	0.51	1.07	99.99
7	62.69	3.08	5.11	24.11	2.98	0.37	0.52	1.13	99.99
8	63.99	2.85	4.84	23.84	2.71	0.34	0.45	0.98	100.00
9	62.93	3.04	5.10	24.08	2.99	0.37	0.36	1.11	99.98
10	62.95	2.89	5.08	23.66	3.51	0.44	0.48	0.99	100.00

Table 5
Calculated chemical composition and prognosed compressive strength of clinker from Table 2

	Oxides content (mass %)					Prognosed compressive strength (MPa)	
N	CaO (X5)	Fe_2O_{3C} (X6)	Al_2O_3 (X7)	SiO_2 (X8)	Fe_2O_{3C}[a]	y28[a]	y180[a]
1	63.85	7.71	4.84	22.90	10.26	44.52	57.71
2	60.76	11.05	3.62	22.58	14.70	48.15	61.91
3	62.78	6.94	4.86	23.82	9.23	43.28	56.03
4	62.23	8.37	5.11	22.92	11.13	45.62	58.74
5	61.44	8.85	5.25	23.16	11.76	46.04	59.22
6	61.24	8.70	5.20	23.41	11.58	46.31	59.35
7	61.87	7.75	5.04	23.79	10.31	46.01	58.75
8	63.22	7.10	4.79	23.56	9.45	45.08	57.85

[a] $Fe_2O_{3C} = (1.43F + 1.111FeO + Fe_2O_3)1.33$.

$$Fe_2O_{3C} = 1.43F + 1.111FeO + Fe_2O_3 \quad (1)$$

Table 6
Chemical composition of clinker

	Oxides content (mass %)							Clinker module			
N	CaO	Fe_2O_{3E}	Al_2O_3	C_f[a]	SiO_2	MnO	Cr_2O_3[a]	LCF	SR	Fe_2O_{3D}	Fe_2O_{3D}[a]
1	65.00	9.80	3.40	1.4	20.20	0.60	0.30	0.99	1.53	21.4	4.70
2	62.30	13.00	3.40	0.2	20.10	0.68	0.34	0.92	1.22	15.0	13.7
3	64.50	9.50	3.70	1.0	20.90	0.76	0.34	0.94	1.58	26.9	2.84
4	64.50	10.40	3.00	0.8	21.30	0.62	0.30	0.94	1.54	19.5	7.02
5	62.70	11.30	3.90	0.6	20.40	0.60	0.32	0.91	1.32	21.7	4.07
6	62.70	11.20	3.60	0.6	21.10	0.70	0.34	0.89	1.42	22.3	3.39
7	63.30	10.70	3.20	0.4	20.80	0.75	0.34	0.93	1.50	27.6	3.64
8	64.50	9.60	3.60	1.1	21.30	0.64	0.30	0.92	1.61	26.0	1.65
9	63.00	11.00	3.60	0.4	21.00	0.73	0.34	0.90	1.44	29.7	
10	64.30	10.40	3.10	0.7	20.40	0.65	0.31	0.97	1.57	19.2	

[a] $C_f = CaO_{free}$; Fe_2O_{3E} = obtained from chemical analysis of clinker produced; $Fe_2O_{3D} = \{(Fe_2O_{3E} - Fe_2O_{3C})100\}/Fe_2O_{3E}$.

presence of less than 1.0 mass % of Fe and FeO in the raw mix components may not alter the chemical composition of clinker to be produced.

At high Fe and FeO content, there is the need to consider the influence of the oxidation process during calculation of Fe_2O_3 (Table 5). Comparative analysis of Fe_2O_{3D} contents in Table 6 showed that the difference between the calculated values using the above Eq. (1) and the experimental ones were about 15–30%. Taking this and the reaction stoichiometry into account [11], it was necessary to find a correction coefficient to account for the variation. Based on observation, it was decided that the approximate value of Fe_2O_3 produced from raw mix containing metallic particles can be obtained by multiplying Eq. (1) by a coefficient of 1.3 – 1.4. Calculation of the Fe_2O_{3C}[a] based on the proposed modification of Eq. (1), for raw mix containing more than 2 mass % metallic particles, showed a high level of accuracy as represented in Fe_2O_{3C}[a] and Fe_2O_{3D}[a] (Tables 5 and 6). The same cannot be said of the calculated compressive strength based on the obtained regression equation (Tables 2 and 5). Consequently, the calculation of Fe_2O_3 can be: $Fe_2O_3 = (1.43F + 1.11FeO + Fe_2O_{3initial})(1.3 - 1.4)$ — for raw mix containing more than 2 mass % metallic particles and $Fe_2O_3 = (0.0143F + 0.0111FeO + Fe_2O_{3initial})(1.3 - 1.4)$ — for raw mix containing less than 2 mass % metallic particles.

Early prognosis of the Fe_2O_3 content in the raw mix could greatly influence the optimization process and the determination of the composition suitability for clinkerization. The ability to effectively control the composition of the raw mix from by-products containing metallic particles will greatly enhance not only their utilization but also the production of more reactive cement at lower temperature.

3.1. Assessment of proposed equations

Based on the proposed equation, the Fe_2O_3 content of the clinker from raw mix containing burnt abrasive slurry (Table 8) and the expected compressive strength (Table 3) were calculated. The computation program is as presented below. Comparative analysis of the experimentally obtained compressive strength values and those obtained using the proposed equations showed remarkable agreement with a maximum deviation of 8.5%. For raw mix containing high concentration of metallic particles (Table 2), computation of its Fe_2O_3 content showed a high degree of agreement with experimental values; however, for the determination of compressive strength, the same cannot be said (Tables 2 and 6).

```
INPUT "COMPOSITION OF FE (1–55%)"; FE
'X61FEO
```

Table 7
Calculated chemical composition of raw mix

	Oxides content (mass %)								
N	CaO	Fe_2O_3	Al_2O_3	SiO_2	Fe	FeO	Cr_2O_3	MnO	Total
1	65.22	4.08	4.57	24.16	0.32	0.29	0.43	0.99	100.06
2	63.24	4.40	5.62	24.23	0.47	0.42	0.48	1.13	99.99
3	64.31	4.25	6.00	23.13	0.63	0.53	0.35	0.72	99.92
4	65.32	4.07	4.95	23.67	0.42	0.38	0.35	0.82	99.98
5	64.19	4.28	5.60	23.63	0.50	0.48	0.40	0.89	99.97
6	63.07	4.33	5.91	23.43	0.57	0.52	0.37	0.93	99.13

Table 8
Calculated chemical composition of clinker

	Oxides content (mass %)			
N	CaO	Fe_2O_3[a]	Al_2O_3	SiO_2
1	65.07	5.44	4.07	24.10
2	63.09	5.86	4.48	24.17
3	64.00	5.67	4.23	23.02
4	65.18	5.43	4.06	23.62
5	64.02	5.71	4.26	23.56
6	62.88	5.91	7.29	23.40

[a] $Fe_2O_3 = (0.0143Fe + 0.0111FeO + Fe_2O_{3initial})1.33$.

Table 9
Chemical composition of clinker

	Oxides content (mass %)				Clinker modules		
N	CaO	Fe_2O_{3E}	Al_2O_3	SiO_2	LCF	SR	AR
1	66.1	4.4	4.4	23.1	0.91	2.62	1.00
2	64.9	5.6	4.7	23.4	0.87	2.27	0.84
3	64.7	5.9	4.6	21.8	0.92	2.07	0.78
4	65.6	4.8	4.4	22.2	0.93	2.44	0.89
5	65.6	5.6	4.6	22.6	0.91	2.21	0.82
6	65.2	5.9	4.8	22.7	0.89	2.12	0.81
7	65.1	5.8	4.8	23.0	0.88	2.17	0.82
8	65.5	5.3	4.7	22.3	0.92	2.33	0.88
9	65.9	4.9	4.5	23.2	0.90	2.46	0.92
10	65.4	5.4	4.8	23.0	0.89	2.25	0.89

No free CaO present.

```
INPUT "COMPOSITION OF FEO (2–10%)"; FEO
'X62FEO
INPUT "COMPOSITION OF FE2O3 (3–6%)"; FE2O3
'X63FE2O3
X6=((1.43*FE)/100+(1.111*FEO)/100)*1.33 + FE2O3
'X6=(1.43*FE + 1.111*FEO + FE2O3)*1.33
PRINT "OXIDE CONTENT OF X6 = "; X6
'INPUT "COMPOSITION OF X5 (55–65)"; X5
'X5 = CALCIUM OXIDE CAO
INPUT ''COMPOSITION OF X7 (3–6)''; X7
'X7 = ALUMINIUM OXIDE AL2O3
INPUT "COMPOSITION OF X8 (22–24)"; X8
'X8 = SILICON OXIDE SIO2
X5 = 100 – (X6 + X7 + X8)
PRINT "X5 = "; X5; "%"
'COMPOSITION OF RAW MIX
INPUT ''LIMESTONE COMPOSITION (0.75–
0.85)%"; RX1
INPUT ''OPEN-HEARTH SLAG COMPOSITION
(0.04–0.09)%"; RX2
RX3 = X6*.01 'RX3 = ABRASIVE SLURRY
RX4=.09 'RX4 = SAND
'Y28. = 40.12*RX1 + 33.73*RX2 + 34.54*R-
X3 + 13.54*RX1*RX2 + 30.08*RX1*RX3 + 33.61*R-
X2*RX3 + 188.97*RX1*RX2*RX3 + 62.48*RX1*R-
X2*(RX1 – RX2) + 6.41*RX1*RX3*(RX1 – R-
RX3) + 87.52*RX2*RX3*(RX2 – RX3)
'Y2. = 40.12*RX1 + 33.73*RX2 + 34.54*RX3 + 13.54*-
RX1*RX2 + 30.08*RX1*RX3 + 33.61*RX2*RX3 -
– 188.97*RX1*RX2*RX3 – 62.48*RX1*RX2*(RX1 -
– RX2) + 6.41*RX1*RX3*(RX1 – RX3) – 87.52*R-
87.52*RX2*RX3*(RX2 – RX3)
'Y180 = 52.5*RX1 + 46.7*RX2 + 52.5*RX3 + 1.68*R-
X1*RX3 + 19.55*RX1*RX3 + 26.43*RX2*R-
X3 + 172.41*RX1*RX2*RX3 + 56.81*RX1*RX2*(R-
X1 – RX2) + 41.78*RX1*RX3*(RX1 – RX3) + 73.19*-
3.19*RX2*RX3*(RX2 – RX3)
'Y18 = 52.5*RX1 + 46.7*RX2 + 52.5*RX3 – 1.68*R-
RX1*RX3 + 19.55*RX1*RX3 + 26.43*RX2*RX3 -
– 172.41*RX1*RX2*RX3 + 56.81*RX1*RX2*(RX1 -
– RX2) + 41.78*RX1*RX3*(RX1 – RX3) – 73.19*R-
73.19*RX2*RX3*(RX2 – RX3)
Y28 = 52.5*RX1 + 57.5*RX2 + 50.2*RX3 + 0.11*R-
X2 + 11.47*RX1*RX2 + 7.44*RX2*RX3 + 216.27*R-
X1*RX2*RX3 + 27.78*RX1*RX2*(RX1 – R-
RX2) + 13.72*RX1*RX3*(RX1 – RX3) + 25.8*RX2*R-
RX3*(RX2 – RX3)
Y2 = 52.5*RX1 + 57.5*RX2 + 50.2*RX3 + 0.11*R-
X2 + 011.47*RX1*RX2 + 07.44*RX2*RX3 + 216.27*R-
X1*RX2*RX3 + 27.78*RX1*RX2*(RX1 – R-
RX2) + 13.72*RX1*RX3*(RX1 – RX3) – 25.8*RX2*-
RX2*RX3*(RX2 – RX3)
PRINT "STRENGTH OF CEMENT = "; Y28; Y28.;
Y180; "%"
PRINT "ALTERNATE STRENGTH OF CEMENT = ";
Y2; Y2.; Y18; "%"
END
```

4. Conclusion

Currently used characteristic formulae for optimization of PCC raw mix can be applied for cement raw mix component containing less than 1 mass % metallic particles; however, the expected Fe_2O_3 content should be predicted using the formula:

$$Fe_2O_3 = (0.0143F + 0.0111FeO + Fe_2O_{3initial})(1.3 - 1.4).$$

Regression equation developed for determining the compressive strength for raw mix containing less than 1 mass % metallic particles showed a high degree of accuracy when compared with experimental values. For raw mix containing more than 2 mass %, the expected Fe_2O_3 content could be predicted using the formula:

$$Fe_2O_3 = (1.43F + 1.11FeO + Fe_2O_{3initial})(1.3 - 1.4).$$

However, determination of the compressive strength via the proposed equations showed much discrepancy.

References

[1] M.M. Nikolaev, Y.M. Butt, V.V. Timashev, Sintering of alite-aluminoferrite clinker, Investigation Into Chemistry and Technology of Silicate, Moscow Chemico-Technology Inst., Moscow, 1964, pp. 25–29.

[2] V.V. Timashev, Y.M. Butt, Crystal formation in portland cement raw mixes during sintering, Proc All Union Conf on Chemistry and Tech of Cement, Stroiizdat Moscow, 1967, pp. 52–87.

[3] P.Y. Zhou, 9th Intern Congress on the Chemistry of Cement, New Delhi LOC, New Delhi, Vol. II (1992) 271–277.

[4] V. Riganti, A. Fiamara, G.B. Odobez, Waste Manage Res 6 (4) (1986) 293–302.

[5] J.O. Odigure, Kinetic modelling of cement raw mix containing iron particles and clinker microstructure, Cem Concr Res 26 (1996) 1435–1442.

[6] J.O. Odigure, Mineral composition and microstructure of clinker from raw mix containing metallic particles, Cem Concr Res 26 (1996) 1171–1178.
[7] J.O. Odigure, Hydration of cement paste and concrete from raw mix containing metallic particles, Cem Concr Res 24 (1994) 1549–1557.
[8] Y.M. Butt, M.M. Cichev, V.V. Timashev, Chemical Technology of Binding Materials, Vishaya Shola Publication, Moscow, 1980 (472p).
[9] A.K. Chatterjee, Chemico-physio-mineralogical characteristics of raw materials, in: S.N. Ghosh (Ed.), Advances in Cement Technology, Pergamon, NY, 1983, pp. 39–68.
[10] J.O. Odigure, Preparation of cement raw mix containing metallic particles, Cem Concr Res 27 (1997) 1641–1648.
[11] B.V. Necrasov, Basic General Chemistry, T. 2, Ximiya Publication, Moscow, 1970, T. 2, pp. 262, 391–398; T. 3, pp. 341–354.
[12] D.C. Montgomery, Design and Analysis of Experiments, Wiley, Canada, 1991, pp. 551–558.