Wear minimisation in concrete with haematite

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Haematite served as a replacement at 15, 30, 45 and 60 vol.-% for typical limestone based aggregates. Wear tests were performed on those specimens under 100, 200 and 300 kPa compression. A statistical response surface method (RSM) was used to evaluate the effects of concentration of cement and haematite on wear. The method allows among others optimisation of the haematite content with respect to wear. For a fixed content of cement, RSM tells us to increase the content of haematite to lower wear.

Keywords: Wear, Concrete, Haematite, Response surface method

Introduction

Real life decision making frequently requires that a compromise be reached between conflicting objectives. The compromises required to strike a balance between wealth and quality of life, between performance and the cost of a car or between health and pleasure of eating rich foods, are familiar ones. Similar conflicts arise in the production and design of composite materials, such as abrasive wear resistant concretes.[1] Concrete is a composite material in which the ingredient consists of water, cement, aggregate and chemical and mineral admixtures. Moreover, it is one of the principal materials for structures and widely used all over the world as construction material. Very extensive literature on concretes includes a number of reviews.[2–7] Cement is usually the binder materials of concrete. However, polymer concretes, in which binders are polymeric resins, have been developed recently.[8] Interface phase is very important for the properties of multiphase composites as concrete. Kopczynska and Ehrenstein[9] discussed the determining effect of interfaces on the properties of multiphase materials. Although compressive strength is the most important concrete parameter and the main parameter for quality control, the abrasive resistance of construction materials, including mortar and concrete, with cement binders, is very important for their service life, especially in industrial enterprises.

Wear resistant concrete is required for many applications such as pavements, floors and concrete highways, hydraulic structures such as tunnels and dam spillways or other surfaces upon which abrasive forces are applied between surfaces and moving objects during service.[10]

In order to arrive at minimum cost design within reasonable amount of time, a method based on certain optimality criteria becomes necessary. The main problem in the successful optimisation of wear resistant concrete parameters is the derivation of high quality analytical equations that can be used to predict concrete parameters. The most widely used approach in the literature for prediction purposes is the classical regression analysis. The prediction ability of regression analyses may be limited for highly non-linear problems.[11] Moreover, artificial neural networks have been widely used in the literature due to their high prediction performance.[12,13] The problem with neural networks is their black box-like working characteristic. It is not easy to relate inputs of an artificial neural network with its outputs in an analytical equation form.

In this study, a multiobjective simultaneous optimisation technique is used to optimise concrete with special emphasis on wear, in which the response surface method (RSM) is incorporated. The RSM uses statistical techniques for empirical model building; it comprises regression surface fitting to obtain approximate responses, design of experiments to obtain minimum variances of the responses and optimisations using the approximated responses. The RSM also aims to reduce the cost and numerical complexity of other expensive analysis methods such as finite element and finite difference methods.[14,15] The RSM has been widely used to optimise products and processes in manufacturing, chemical and other industries, but it has had very limited use in the concrete industry. In one study, Simon *et al.*[16] optimised high performance concrete mixtures using this method. Bayramov *et al.*[17] optimised the fracture parameters of steel fibre reinforced concrete to obtain a more ductile behaviour.

As far as we know, no study has been carried out to utilise the RSM technique in optimising the abrasion wear of concrete. The purpose of the present study is to optimise the abrasive wear of concrete proportioned with different cement contents and haematite aggregates under different loads applied.

The main objective of this research was to determine the effects of both cement and haematite content on the wear of concrete and to find the optimum solutions by means of a multiobjective simultaneous optimisation technique in which dependent and/or independent variables were simultaneously maximised or minimised. For this purpose, wear of concrete was minimised simultaneously at the

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Received 3 March 2012; accepted 27 April 2012
DOI 10.1179/1433075X12Y.0000000034

minimum cement and haematite content at each load of wear test using the experimental results. Thus, optimal values for the mix design parameters, such as cement and haematite content, were found while the abrasive wear of concrete is minimised.

Experimental

Materials and mixture proportions

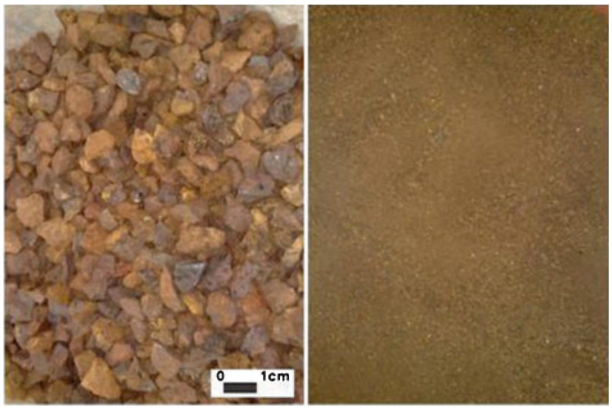
We have produced plain concrete using limestone based aggregates labelled as crushed stone I (CSt-I), natural river stone (NRS) and crushed stone II (CSt-II). The aggregates were graded, washed and cleaned of clay and silts. To reduce difficulties of producing, mixing and placing of concretes and to prevent segregation of heavyweight aggregate in fresh concretes, the maximum aggregate size was selected as 16 mm diameter. Gradation of aggregates is presented in Table 1.

Haematite was adopted as a replacement for concrete aggregates. Haematite is a natural red rock that contains iron oxide; when pure, it has Mohs hardness between 5·5 and 6·5 and specific gravity between 4·9 and 5·5 g cm^{-3}. However, the physical properties of rocks in which haematites are the main constituent may vary considerably; the specific gravity of haematite ores can range between 3·2 and 4·3 g cm^{-3}. Some ores are soft and produce dust in the course of being handled, which would make them a poor aggregate for heavy concrete. Haematite particles tend to be flaky, which is undesirable with regard to the workability of concrete.[18]

Haematite was prepared as aggregate by crushing and grounding the ore in a laboratory mill and then sorting it via sieves into two groups of coarse (H_c) and fine (H_f) aggregates (Fig. 1). Afterwards, haematite aggregate was filtered to have the same grading curve as the mixture curve. Specific gravity, water absorption and loose and dry rodded unit weights were determined according to ASTM C 127,[19] ASTM C 128[20] and ASTM C 29[21] standards. The physical and mechanical properties of all aggregates are presented in Table 2. The chemical composition of haematite is presented in Table 3.

The cement used in all the concrete mixtures was a normal Portland cement which corresponds to CEM II/A-M (P-LL) 42·5 N Portland cement. The physical and mechanical properties and chemical analysis of cement are presented respectively in Tables 4 and 5. A superplasticiser (SP) based on a modified polycarboxylate was employed to obtain a satisfactory workability for each mix. The SP has specific gravity, pH and solid content of 1·08 g cm^{-3}, 5·7 and 40% respectively.

The water/cement (w/c) ratio typically used is 0·30–0·50 for heavyweight concretes.[22] Mixtures of concrete were chosen with a single value in the middle of that range, that is, w/c=0·40. Four main groups according to cement contents and five subgroups (Table 6) under each main group according to haematite volumes in the mixes were divided. Cement dosages were accepted as 300, 350, 400 and 450 kg m^{-3}.



1 Coarse (left) and fine (right) haematite aggregates

We have used 15, 30, 45 and 60 vol.-% replacement ratios of haematite aggregate to examine the effect of metallic aggregate instead of limestone based aggregates. The masses of used materials in the final mix design to obtain 1 m^3 of concrete for each mix proportion are given in Table 6.

Specimen preparation

In a typical mixing procedure, the materials were placed in a laboratory mixer with capacity of 60 dm^3 in the following sequence: first coarse aggregates, fine aggregates followed by cement, initially dry material mixed for 1 min and finally addition of 80% of water. After 1·5 min of mixing, the rest of the mixing water was added. All batches were mixed for a total time of 5 min.

The initial mixing time is more important for polycarboxylate based admixtures due to their dispersing mechanism. In order to sustain the equilibrium viscosity, longer mixing times are required. However, due to the high density of haematite, segregation is a danger. In order to prevent fresh concrete from segregation, the mixing duration was kept as low as possible. For each mixture, good workability and sufficient strength gain were achieved.

After the mixing procedure was completed, six cubic samples (150 × 150 × 150 mm) were cast. The cubes were used for compressive strength determination. After casting, the concrete specimens were covered with wet burlap and polyethylene sheets and kept in the laboratory at room temperature for 24 h. After demoulding, they were placed in a saturated limewater bath until the time of testing. Curing was performed in accordance with ASTM C 511.[23] It is well recognised that adequate curing of

Table 1 Aggregate gradations

	Sieve size									
Codes	16 mm	12·5 mm	9·5 mm	4·75 mm	2·36 mm	1·18 mm	600 μm	300 μm	150 μm	75 μm
CSt-I	100	100	100	99	78	52	34	28	16	11
NRS	100	100	100	85	56	35	20	14	2·4	1
CSt-II	100	91	72	8	2	0·6	0·4	0·4	0·4	0·4
H_f	100	100	100	100	84	64	48	41	22	13
H_c	100	83	53	7	0·5	0·3	0·3	0·2	0·2	0·1

Table 2 Physical properties of aggregates

Aggregate codes	Specific gravity/g cm^{-3}	Water absorption/%	Loose unit weight/kg m^{-3}	Dry rodded unit weight/kg m^{-3}
CSt-I	2·69	2·91	1913	2151
NRS	2·67	3·02	1830	1974
CSt-II	2·7	0·93	1676	1594
H_f	4·18	1·6	1956	2130
H_c	4·29	0·8	1733	1929

concrete is very important not only to achieve the desired compressive strength but also to make durable concrete.

We recall that there are a variety of methods of determination of abrasion.[24,25] Abrasion resistance tests were performed using Bohme method. In our case, samples of $70\times70\times70\times1{\cdot}5$ mm (50 cm^2 cross-sectional area) were used for the determination of wear resistance at 28 days according to Turkish standard specifications TS 699.[26] Although this standard is highly recommended for abrasion of natural stones, it is applied on concrete specimens as an alternative of ASTM C 779.[27] Numerous researchers have used this method and obtained reliable results.[28–31]

Test procedure

The compressive strength tests were carried out in accordance with ASTM C 39[32] at 28 days. In compliance with TS 699, the abrasion system had a steel disc with diameter of 750 mm and rotating speed of 30 ± 1 cycle/min, a counter and a lever. The abrasion test apparatus is shown in Fig. 2. In the test procedure, $20\pm0{\cdot}5$ g of abrasion dust was spread on the disc, the specimens were then placed, loads of 5, 10 and 15 kg that equal to pressures of 100, 200 and 300 kPa respectively were applied to the specimen and the disc was rotated for four periods; a period was equal to 22 cycles. After that, the surfaces of the disc and the sample were cleaned. The above mentioned procedure was repeated for each edge of concrete samples (totally 440 cycles) by rotating the sample 90° in each period. The wear loses are calculated after at least 440 traversals over the same track. The volume decrease was measured in cm^3 cm^{-2} and assigned to wear. Abrasive dust used was corundum (crystalline Al_2O_3).

Table 3 Chemical composition of haematite

Compound	Content/wt-%
Fe_2O_3	82·3
MnO	0·13
MgO	1·54
TiO_2	0·03
Al_2O_3	0·57
CaO	4·68
SiO_2	4·15
LOI*	5·63

*Loss of ignition.

Compressive strength

Compressive strengths values are presented in Fig. 3. As expected, compressive strength is affected by both cement content and haematite content.

Increment in cement and haematite content increases the compressive strength of concrete. The compressive strength was also increased up to 65 MPa, depending on the cement content in the mixture. Oluokun and Malak[33] reported that the incorporation of ilmenite and haematite coarse aggregates into concrete mixes appeared to significantly increase the compressive strength, enhance the stress–strain behaviour and result in the production of tougher and more ductile concrete

Regression analysis with RSM

Analysis of response surface involves choosing a model that fits the experimental data and testing the adequacy of the fitted model. A response surface is the diagram of system dependent variables or responses as a function of one or more independent variables or factors. The response surface presents a visual analysis of how certain factors influence the responses. After building a model, the optimisation procedure is performed using the response surface of that model as the basis for finding the best solution. Without establishing a model, optimisation does not lead to a general solution of the problem. Therefore, it is necessary to have some experimental data for building a model.

As noted above, our aim was to provide the optimisation by maximising the wear of concrete (*Wear*) at minimum cement content (V_c) and haematite content (V_h) for different loads in wear testing (P_w). For this purpose, a statistical RSM was used for the modelling and analysis of data experimentally obtained.[17]Two factors (or independent x_k design variables) that can be selected to define this system are cement content ($x_1=V_c$), and haematite volume fraction ($x_2=V_h$) for each category. For each category, reasonable ranges can be given as follows

$$300\ \text{kg}\le V_c\le 450\ \text{kg}$$

$$0\%\le V_h\le 60\%$$

A common response surface experimental plan that can be used as a means to find optimal settings is a two-variable (i.e. V_c and V_h) and a four-level for V_c (i.e. V_c=300, 350, 400 and 450 kg) and a five-level for V_h (i.e.

Table 4 Physical and mechanical properties of Portland cement

Compressive strength/MPa			Flexural strength/MPa			Initial setting time/h	Final setting time/h	Le Chatelier/ mm	Specific gravity/g cm^{-3}	Blaine/ cm^2 g^{-1}
2 days	7 days	28 days	2 days	7 days	28 days	2·25	3·15	1	3·15	4150
22·5	36·6	47·8	3·7	5·6	6·9					

Table 5 Chemical analysis of Portland cement

Compound	Content/wt-%
Total SiO_2	22·9
Al_2O_3	5·32
Fe_2O_3	3·63
CaO	55·83
MgO	1·99
SO_3	2·62
Cl	0
LOI*	4·2
Free CaO	0·82
Total Admixture	19·45

*Loss of ignition.

V_h=0, 15, 30, 45 and 60%). The design for two independent variables consists of $4\times5=20$ mixtures for each category (i.e. P_w=100, 200 and 300 kPa), as shown in Fig. 4.

The use of four-level V_c, five-level V_h and the two variable experimental designs allows the estimation of a mathematical model for the response of *Wear*. Generally, the structure of the relationship between the response and the independent variables is unknown. The first step in RSM is to find a suitable approximation to the true relationship. For most of the response surfaces, the functions for the approximations are low order polynomials (first or second order) because of simplicity, though the functions are not limited to the polynomials.[14]

In each category (loading of wear test), 20 experimental data for each response of wear were fitted to a cubic type model using analysis of variance. For each category, the fitted regression models for the wear of concrete (*Wear*) are given below.

For the wear test loading of 100 kPa

$$Wear = 7.87 - 3.15\times10^{-3}V_c - 0.47V_h + 6.66\times10^{-5}V_cV_h + 0.014V_h^2 - 1.33\times10^{-4}V_h^3 \quad (1)$$

For the wear test loading of 200 kPa

$$Wear = 12.44 - 3.15\times10^{-3}V_c - 0.61V_h + 6.66\times10^{-5}V_cV_h + 0.016V_h^2 - 1.33\times10^{-4}V_h^3 \quad (2)$$

2 Test apparatus

For the wear test loading of 300 kPa

$$Wear = 16.93 - 3.15\times10^{-3}V_c - 0.75V_h + 6.66\times10^{-5}V_cV_h + 0.017V_h^2 - 1.33\times10^{-4}V_h^3 \quad (3)$$

The correlation coefficient for equations (1)–(3) was determined as 0·99. Regression models obtained using the RSM for the wear of concrete at each category are shown in Figs. 5–7. A diagram of the average actual value versus predicted value (average value of three categories) is also given in Fig. 8.

Optimisation

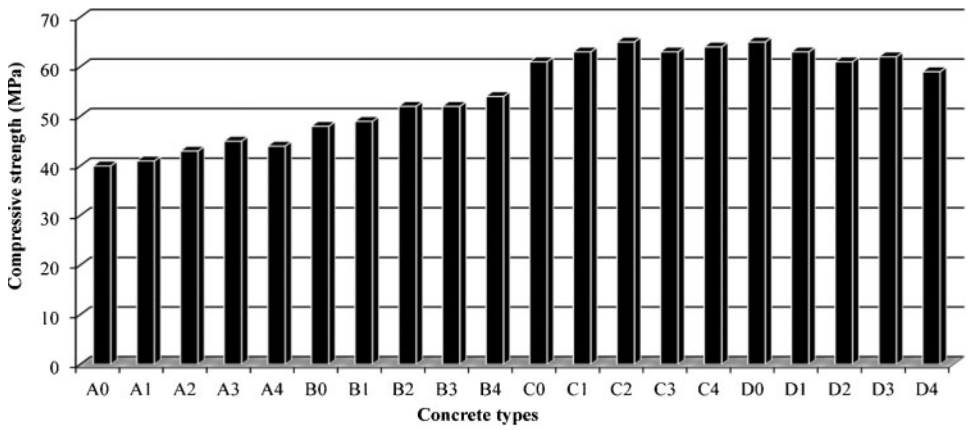
In order to optimise the responses simultaneously, a numerical optimisation technique using desirability functions (d_j), which are defined for each response, can be used.[34] A desirability function (d_j) varies over the range of $0\leqslant d_j\leqslant 1$. A multiobjective optimisation problem is solved using the single composite response (D) given in equations (1)–(3), which is the geometric mean of the individual desirability functions

$$D = (d_1\times d_2\times d_3\times \ldots \cdot d_4)^{1/n} \quad (4)$$

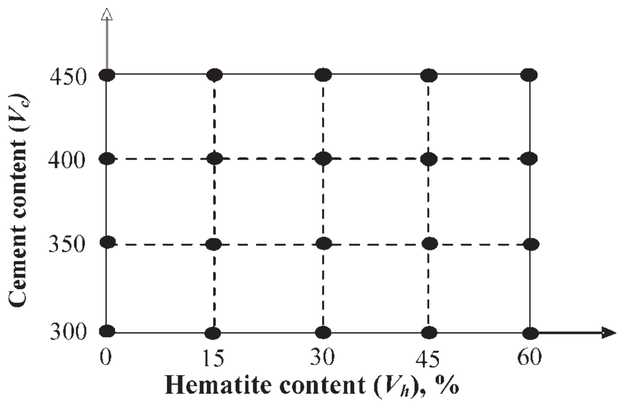
where n is the number of responses included in the optimisation. Appropriate regions of V_c and V_h have been defined above.

Table 6 Mixture proportions

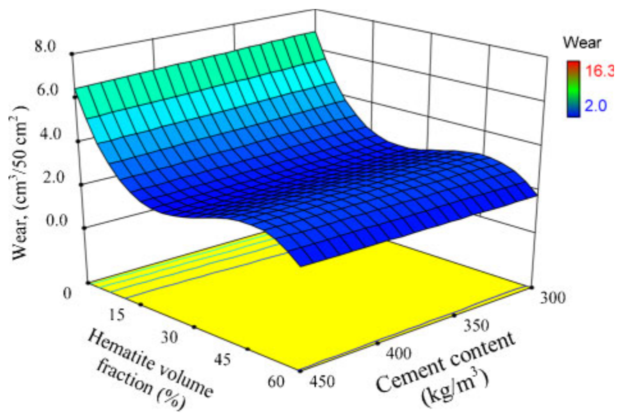
Haematite ratio/%	Cement/kg m^{-3}	Water/kg m^{-3}	SP/kg m^{-3}	CSt-I/kg m^{-3}	NRS/kg m^{-3}	CSt-II/kg m^{-3}	H_f/kg m^{-3}	H_c/kg m^{-3}
0	300	117·0	3·0	528	524	1060	0	0
15	300	117·0	3·0	449	445	901	246	253
30	300	117·0	3·0	370	367	742	492	505
45	300	117·0	3·0	290	288	583	738	758
60	300	117·0	3·0	211	210	424	984	1010
0	350	136·5	3·5	504	500	1011	0	0
15	350	136·5	3·5	428	425	859	235	241
30	350	136·5	3·5	353	350	708	470	482
45	350	136·5	3·5	277	275	556	705	723
60	350	136·5	3·5	201	200	404	939	964
0	400	156·0	4·0	480	476	963	0	0
15	400	156·0	4·0	408	401	819	224	230
30	400	156·0	4·0	336	333	674	447	459
45	400	156·0	4·0	264	262	530	671	689
60	400	156·0	4·0	192	191	385	894	918
0	450	175·5	4·5	456	452	915	0	0
15	450	175·5	4·5	387	384	777	212	218
30	450	175·5	4·5	319	317	640	425	436
45	450	175·5	4·5	251	249	503	637	654
60	450	175·5	4·5	182	181	366	850	872



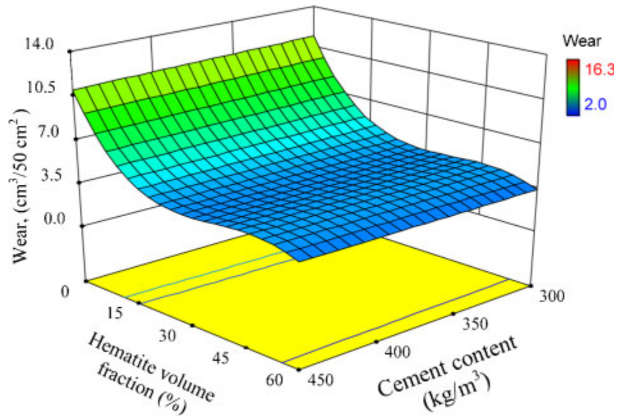
3 Compressive strengths of concretes



4 Experimental design points for wear of concrete (P_w=100 kPa, 200 kPa and 300 kPa)



5 Response surfaces for models in equation (1) (P_w=100 kPa)



6 Response surfaces for models given in equation (2) (P_w=200 kPa)

The cost of the concrete mix used in the production of concrete, which is resistant to wear, is also important. Therefore, it is necessary to minimise *Wear*, V_c and V_h simultaneously. For n=3, equations (4) takes the form

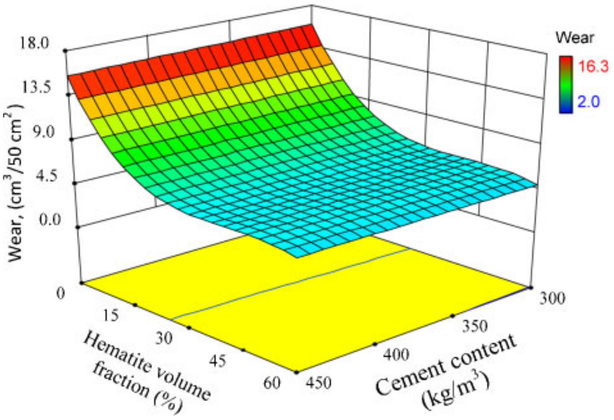
$$D=(d_1 \times d_2 \times d_3)^{1/3} \tag{5}$$

where d_1, d_2 and d_3 are the desirability functions of *Wear*, V_c and V_h respectively. For each loading of wear test, the solutions of this multiobjective optimisation are shown in Table 7.

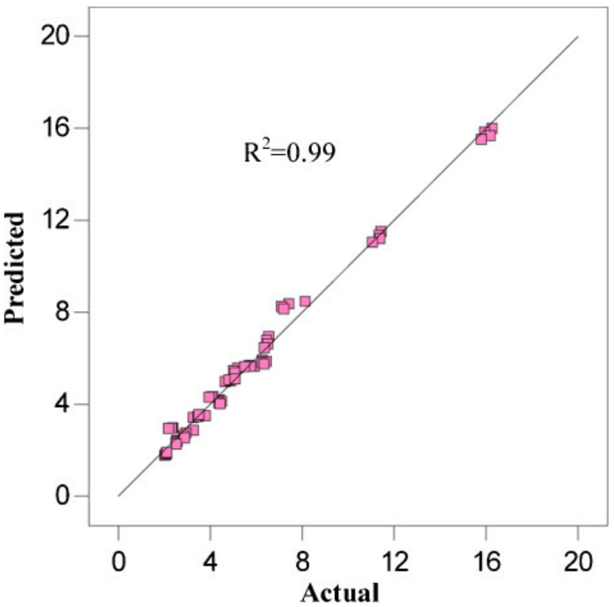
We keep the cement content at 300 kg since cement is the most expensive component of concrete; higher amounts of cement would increase the cost. To appreciate the results presented in Table 7, let us make for a moment a simple assumption that wear should be proportional to the load applied. We have determined wear under three loads. Under the lowest load of 100 kPa, we

Table 7 Optimum solutions for different P_w when *Wear*, V_c and V_h are minimised

	Target	Limits		Optimum solutions with respect to P_w		
		Lower	Upper			
Loading of wear test P_w/kPa	100; 200; 300	100	300	100	200	300
Cement content V_c/kg	Minimum	300	450	300	300	300
Haematite content V_h/%	Minimum	0	60	8·6	14·3	19·3
Wear of concrete *Wear*/cm^3/50 cm^2	Minimum	2·0	16·3	4·0	5·8	7·3



7 Response surfaces for models given in equation (3) (P_w=300 kPa)



8 Actual values versus predicted values (average value of three categories) for wear of concrete

have the wear of 4·0 cm^3/50 cm^2. Doubling the load, instead of 8·0 in the same units, we only have the wear equal to 5·8. This is related to the fact that the optimised mixture for 200 kPa contains more haematite. Similarly, under the highest load of 300 kPa, we have the wear only 7·3 cm^3/50 cm^2 rather than 12 in the same units. Again, the optimised concentration of haematite is higher. The interfacial zone between cement paste and aggregate is the weakest in the material. One recalls the discussions of Desai and Kapral[35] and Kopczynska and Ehrenstein[9] on the importance of interfaces for properties of multiphase composites. One infers that in our case haematite goes preferentially into the interfacial zone reinforcing it.

Survey of results

An increase in haematite volume fraction in the mix results in an increase in compressive strength of concretes. At the same time, lower wear is observed. Thus, haematite aggregate improves the wear of concrete. The cubic regression model is satisfactory for the prediction of wear of concrete. According to our models, haematite content and loading in wear testing are more significant than cement content. Therefore, both haematite content and loading during wearing of concrete should be taken into account in an optimisation based concrete mix design.

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