Effect of metallic aggregate and cement content on abrasion resistance behaviour of concrete

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Many concrete structures are required to have sufficient abrasion resistance, such as dams, canals, roads and floors. The abrasion resistance of concrete may be defined as its ability to resist being worn away by rubbing. Compressive strength and aggregate type are also important factors affecting the abrasive behaviour of concrete. However, very little information on the properties of haematite containing concrete has been reported. The authors report on the abrasion resistance of concrete with four different cement contents (300, 350, 400 and 450 kg m^{-3}) and with haematite as a metallic aggregate with replacement ratios of 15, 30, 45 and 60% under 5, 10 and 15 kg loads. The water/cement ratio was kept constant at 0·40 to evaluate the effects of haematite and cement content. Slump tests were conducted to evaluate the workability of fresh concretes. For hardened concrete samples, mechanical tests such as compressive strength, splitting tensile strength, unit weight and wear resistance were performed. Along with the physical and mechanical properties of concretes, haematite was studied as a mineral. Increasing both cement and haematite content has substantial effects on the strength of the concrete. Polarising microscopy views of the interfaces show that haematite aggregates exhibit greatly improved bond strength. Wear loss of concrete decreases with increasing concentration of haematite, while it increases with increasing cement content. An equation representing wear as a function of cement content, compressive strength and also applied load provides virtually perfect agreement with the experimental results.

Keywords: Metal–matrix composites, Reinforced cement/plaster, Wear, Haematite

Introduction

Abrasive wear is known to occur in pavements, floors and concrete highways, in hydraulic structures such as tunnels and dam spillways, or in other surfaces upon which abrasive forces are applied between surfaces and moving objects during service. The abrasive resistance of construction materials, including mortar and concrete, with cement binders, is very important for their service life, especially in industrial enterprises.[1] Deterioration of concrete surfaces occurs due to various forms of wear, such as erosion (wearing by abrasive action of fluids containing suspended solids), cavitations (wearing by implosion of vapour bubbles in high velocity fluid flow) and simple abrasion (wearing by repeated rubbing or frictional processes) due to various exposures.[2–4] The classical definition of wear in terms of the weight of debris formed is not applicable in situations when there is deformation but little or no debris; therefore, a definition of wear in terms of the results of sliding wear tests has been proposed.[5] In turn, viscoelastic recovery in sliding wear determination has been quantitatively related to brittleness.[6] Specifically for concrete, its abrasion resistance has also been defined in terms of its ability to resist being worn away by rubbing and friction.[7]

The resistance of concrete to wear is influenced by variables such as aggregate properties, surface finish and hardeners or coatings. Concrete wear resistance is known to increase with increasing compressive strength and tensile strength.[8,9] A relationship between the compressive strength and wear characteristics of concrete has been proposed long ago by Bechyne.[10] A number of previous studies reported that the abrasion resistance of concrete is primarily dependent upon its compressive strength. Factors such as air entrainment, water/cement ratio (w/c), type of aggregates and their properties, etc., which affect the concrete strength, therefore, should also influence the abrasion resistance. According to the American Concrete Institute (ACI) Committee 201, the compressive strength of concrete that

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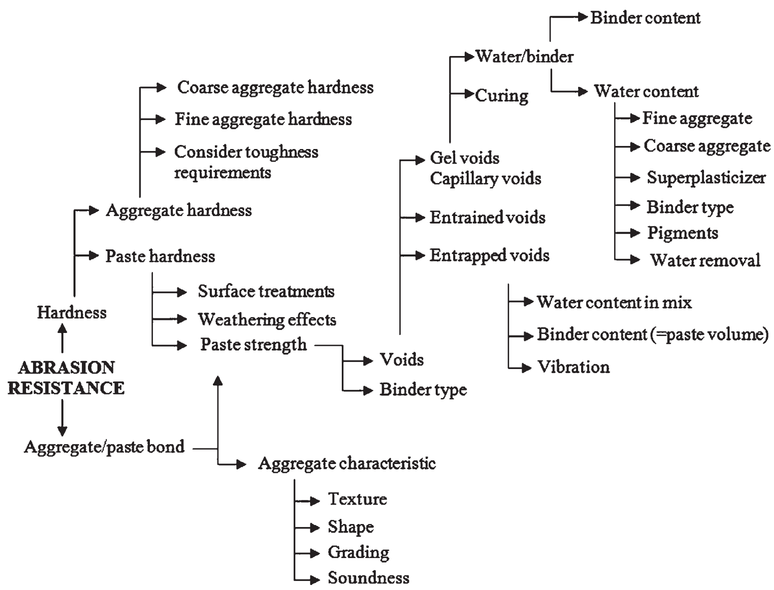


1 **Parameters affecting abrasion resistance of concrete related to hardness and aggregate/paste bonding**

will be subjected to abrasive forces should not be <30 MPa.[3,7] Figure 1 shows how the specific characteristics of various raw materials and the different manufacturing processes all contribute.[11] Soundness is determined by repeatedly submerging an aggregate sample in a saturated solution of sodium or magnesium sulphate. This process causes salt crystals to form in the aggregate pores, which simulates ice crystal formation.

For concrete with high abrasion resistance, it is desirable to use a hard surface material, aggregate and paste with low porosity and high strength.[12] Hardness is important here. On the other hand, high strength concretes with low w/c are less dependent on aggregate type, and the use of a low w/c can provide a dense, strong concrete that is resistant to wear.[8] High strength is made possible by reducing the porosity in homogenous zones and microcracks at the interface between cement paste and aggregate (the transition zone).[13]

In the present study, the performance of haematite and haematite content in concrete was evaluated with respect to strength and abrasion resistance. We applied various levels of haematite replacement with limestone based aggregates. The results obtained should be useful in establishing mixture proportions for wear resistant concretes.

Materials and methods

Aggregates

Since ~75 wt-% of concrete volume is comprised of aggregate, clearly the aggregate properties are important for the overall properties of the concrete.[14] Therefore, we created plain concrete (PC) using limestone based aggregates with three different grain sizes: up to 3 mm size crushed stone (CSt-I), up to 7 mm size natural river stone (NRS) and 7–15 mm size crushed stone II (CSt-II). The aggregates were graded, washed and cleaned of clay and silts. To reduce difficulties of producing, mixing and placing the concretes and to prevent segregation of heavyweight aggregate in fresh concretes, the maximum aggregate size was selected as 16 mm. Results of sieve analysis of fine and coarse aggregates used are presented in Table 1.

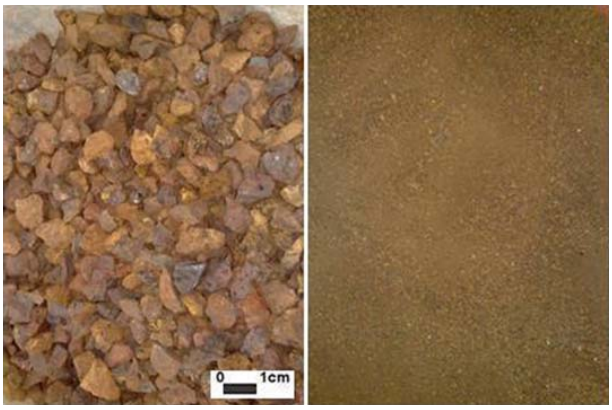
Haematite was prepared as aggregate by crushing and grinding the ore in a laboratory mill and then sorting it via sieves into two groups of coarse H_c and fine H_f aggregates (Fig. 2). Then, the haematite aggregate was filtered to have the same grading curve as the mixture curve.

In this study, haematite was adopted as a replacement for concrete aggregates. Haematite, a natural red rock that contains iron oxide, has a 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. 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 in regard to the workability of concrete.[15]

Specific gravity, water absorption and loose and dry unit weights were determined according to ASTM C127, ASTM C128 and ASTM C129 standards. The physical

Table 1 Particle size distributions of aggregates

	Sieve size									
	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
Aggregate type	Percentage passing/%									
CSt-I	100·0	100·0	100·0	99·1	78·3	51·5	34·1	27·5	15·5	10·7
NRS	100·0	100·0	100·0	84·8	56·1	35·0	20·0	13·6	2·4	1·0
CSt-II	100·0	91·3	72·0	7·5	2·0	0·6	0·4	0·4	0·4	0·4
H_f	100·0	100·0	100·0	100·0	84·4	64·3	48·4	40·8	21·8	13·3
H_c	100·0	82·5	53·0	7·2	0·5	0·3	0·3	0·2	0·2	0·1



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

3 Abrasion test apparatus as specified in TS699

and mechanical properties of all aggregates are presented in Table 2. The chemical composition of the haematite used in this study is presented in Table 3.

Cement

The cement used in all the concrete mixtures was a normal Portland cement according to CEM II/A-M (P-LL) 42·5N. The physical and mechanical properties and the chemical analysis results are presented in Tables 4 and 5 respectively. More than doubling of the compressive strength and nearly doubling the flexural strength were noted between 2 and 28 days.

The Le Chatelier method of cement characterisation is based on using a 30 mm longitudinally split cylindrical mould with two indicators containing the cement paste, exposed to boiling water at atmospheric pressure for 3 h. The cement is acceptable if the distance between the indicators is $\leqslant$10 mm (European Committee on Standardisation).

The Blaine method follows the ASTM C-204-07 standard. The Blaine air permeability apparatus allows drawing a definite quantity of air through a prepared bed of cement of definite porosity. The permeability cell is a rigid cylinder made of stainless steel.

Superplasticiser

A superplasticiser based on a modified polycarboxylic ether was employed to obtain a satisfactory workability for the different mixes. It has a specific gravity of 1·08, pH 5·7 and solid content of 40%.

Mix proportions

To investigate the effect of metallic aggregate on the abrasion resistance of concrete, concretes with haematite and PC were investigated. The absolute volume method developed by the ACI was used in the calculation of the concrete compositions.[16] The used w/c ratios for heavyweight concretes are typically in the range of 0·30–0·50. Therefore, a single w/c ratio equal to 0·40 was chosen. Mixtures were divided into four main groups, A, B, C and D, with 300, 350, 400 and 450 kg m^{-3} of cement, and five subgroups (Table 6) under each main group according to the haematite content. The authors used 0, 15, 30, 45 and 60% replacement ratios of haematite aggregate to examine the effect of metallic aggregate instead of limestone based (L) aggregates. Concrete mixture proportions as mass and volume for 1 m^3 are presented in Tables 6 and 7.

Table 2 Physical properties of aggregates

Aggregate type	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

Mixing, casting, curing and testing

In a typical mixing procedure, the materials were placed in a laboratory mixer with capacity of 60 dm^3 in the following sequence: first aggregates, followed by cement, dry material mixed for 1 min and finally addition of water. After 1·5 min of mixing, chemical admixtures were introduced to the wet mixture.

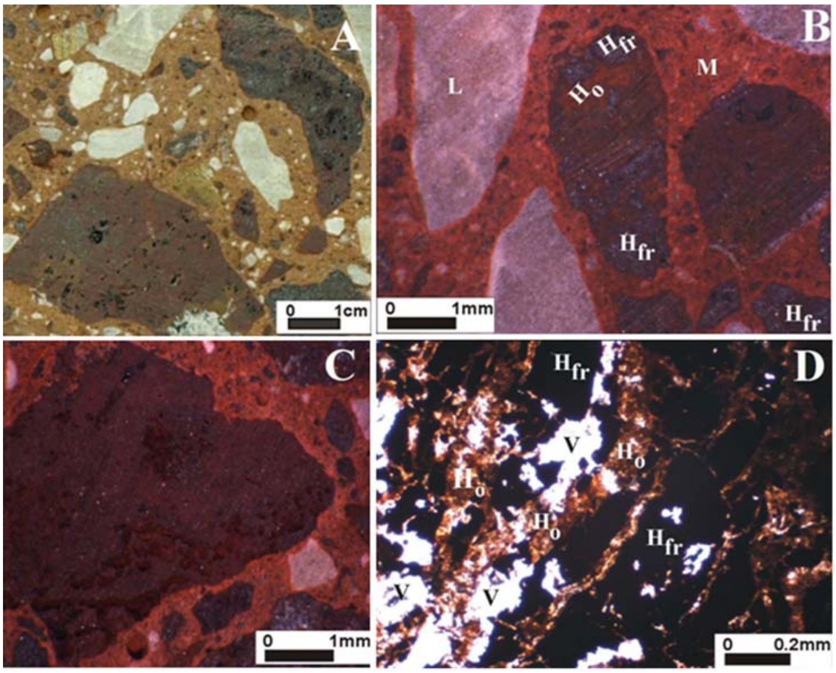
The initial mixing time is more important for polycarboxylate based admixtures due to their dispersing mechanism. In order to sustain equilibrium viscosity, longer mixing times are required. However, because of the high density of haematite, potential segregation is a danger. In order to prevent fresh concrete from segregating, the mixing duration was kept as low as possible. Although good workability was achieved during the fabrication, very little segregation and bleeding were visually observed.

After the mixing procedure was completed, slump tests were conducted on the fresh concrete to determine the workability (ASTM C143). Then, from each concrete mixture, six specimens were cast in three layers in cylindrical moulds of 150 mm diameter and 300 mm height, each layer consolidated using a vibrating table. However, the high specific gravity of haematite is such that excess compacting vibration, which can cause segregation, must be avoided. Casting of specimens was performed according to

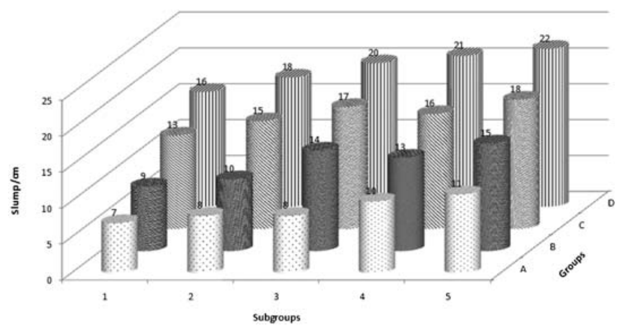
Table 3 Chemical composition of haematite used in this study

Compound	Content/wt-%
Fe_2O_3	82·26
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

*LOI: loss of ignition.



4 Microscopic views of haematite in mixtures with cement content (kg m^{-3}) A, 300; B, 350, C, 400 and D, 450; and subgroups 1–5 presenting haematite % per Table 6



5 Slump values for concretes

ASTM C192. Six 150 mm cubes were cast. The cubes were used for compressive strength, ultrasonic pulse velocity and Schmidt hardness tests, while the cylinders were used for splitting tensile strength and modulus of elasticity 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, the concrete specimens were immersed into lime saturated water until the testing time. After the curing process, all the specimens were stored in laboratory condition at $20\pm2^{\circ}$C and 65% relative humidity (RH) for 24 h and tested at the end of that period. Curing was performed according to ASTM C511.

It is well recognised that adequate curing is very important not only to achieve the desired compressive strength but also to make durable concrete. The compressive strength tests were carried out in accordance with ASTM C39 after 28 days. The splitting tensile strength tests were performed according to ASTM C496 also at 28 days. The same applies to the demoulded unit weight test that was carried out according to ASTM C138.

Samples of $70\times70\times70\pm1{\cdot}5$ mm ($50{\cdot}4$ cm^2 cross-sectional area) were used for the determination of wear resistance at 28 days according to Turkish standard specifications TS699. TS699 is used as an alternative to ASTM C779. Other researchers have used this method and obtained reliable results.[1,12,17,18]

According to TS699, the abrasion system has a steel disc with diameter of 750 mm, a counter and a lever, applying a rotating speed of 30 ± 1 cycles/min. The abrasion testing apparatus can be seen in Fig. 3. Abrasion ($20\pm0{\cdot}5$ g) dust was spread on the disc, and the specimens were then placed there; in turn, loads of 5, 10 and 15 kg were applied to the specimens, and the disc was rotated for four periods, while a period was equal to 22 cycles. After that, the surfaces of the disc and the sample were cleaned. The procedure was repeated for each edge of the concrete samples (440 cycles total) by rotating the sample 90° in each period. The wear losses are calculated after 440 traversals over the same track (cm^3 cm^{-2}). The abrasive dust used in this test was corundum (crystalline Al_2O_3).

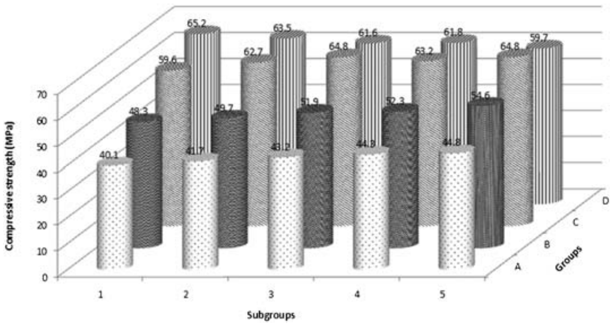
Physical properties of concretes

Along with the physical properties of concrete, haematite was also studied as a mineral.

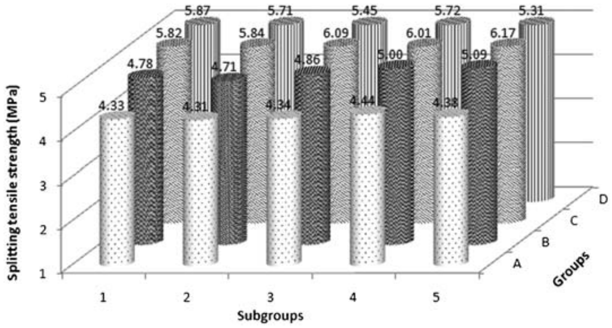
Figure 4*B* and *D* shows that haematite consists of two zones: oxide H_o and fresh H_{fr}. The haematite aggregates

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					



6 Compressive strength determination results



7 Values of splitting tensile strength

have high porosity (Fig. 4*A* and *C*), which is a consequence of voids that have appeared during the formation of haematite. It can be seen that haematite has the form of flakes.

Three factors of mix proportions affect workability: w/c, aggregate/cement ratio and water content. The aggregate/cement ratios were 8·24, 6·74, 5·52 and 4·74 for groups A, B, C and D respectively. As can be seen in Fig. 5, when the aggregate/cement ratio is reduced but the w/c ratio is kept constant, the water content increases; consequently, the workability increases also. Slump of concretes increases with increasing haematite and cement content in each group. D5 had the highest slump of 22 cm.

Increasing haematite and cement content has increased slump due to the high specific gravity of haematite. While a high H_c has a tendency to disturb the mixture homogeneity, very little segregation and bleeding were visually observed during the slump testing.

An important consideration in using results such as in Fig. 5 is that high strength is desired to obtain sufficient workability according to the selected w/c ratio. It is therefore concluded that heavyweight concretes obtained at various haematite and cement contents at 0·40 w/c have high compressive strength and appropriate workability. The slump value of 50 mm is considered an acceptable minimum.[19]

Mechanical properties

Compressive strength

Compressive strength is the most important property of concrete quality. The results of the mixtures in this study are presented in Fig. 6. The inclusion of haematite increases the compressive strength, except for group D, where some segregation is observed visually in fresh concretes from that group. Compressive strength is also dependent on cement content and increases up to 65 MPa. Cement contents in excess of 450 kg m^{-3} cause high and rapid hydration heat, which is a potential cause of cracking.

Consider the interface zone between the cement paste and the coarse haematite aggregate. The surface texture of the coarse aggregate is partly responsible for bonding between the cement paste and the aggregate due to mechanical interlocking, which is important for the properties. Figure 4*A*–*C* shows that the haematite aggregates provide a superior bond, creating a transition zone due to the haematite's porous and rough surface texture. This is desirable for improving the mechanical performance of concrete. Oluokun and Malak[20] 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 with a compressive strength of $\sim$36 MPa. Kopczynska and Ehrenstein[21] discussed the determining effect of interfaces on the properties of multiphase materials.

Results have been reported on the irradiations of reinforcing fibres and concrete.[22–25] Apparently, the mechanical properties of concretes are thus enhanced significantly, an option which is worth noting.

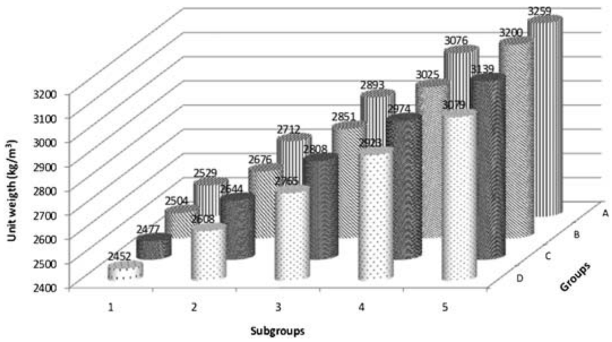
Splitting tensile strength

The results of splitting tensile strength testing for all the materials are presented in Fig. 7. The tensile strength increases when either the cement content or the haematite content increases. The splitting tensile strength values for haematite containing concretes are higher than those for the PCs. Again, we apparently deal with stronger bonding between the cement paste and the aggregate. The splitting tensile strength is more sensitive than the compressive strength to alteration of surface textures of the coarse aggregate.

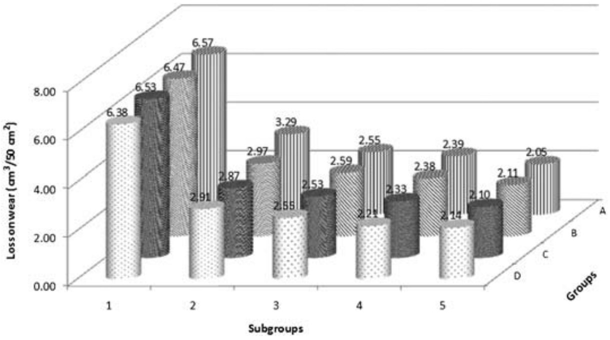
Table 5 Chemical analysis of Portland cement

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

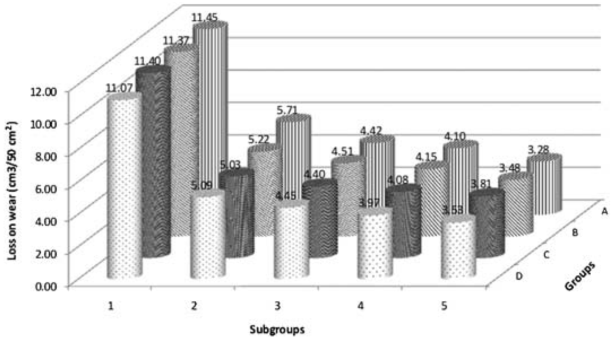
*LOI: loss of ignition.



8 Unit weights of concretes



9 Mass losses of concretes under 5·0 kg load



10 Mass losses of concretes under 10·0 kg load

Unit weight

The results of the unit weight measurements are presented in Fig. 8. For all groups, the unit weight increases with increasing haematite content. At the same time, an increase in cement content decreases the unit weight. The authors recall that the w/c is kept constant; hence, along with an increase in cement content, an increase in water content in the mixture is also obtained. Necessarily, the aggregate volume in the mixture decreases, causing a decrease in unit weight. The aggregate volumes are 0·78, 0·75, 0·71 and 0·68 for groups A, B, C and D respectively. The maximum value is $3{\cdot}26\times10^{3}$ kg m^{-3} in subgroup A5.

Wear resistance

The principal factors affecting the abrasion resistance of concrete can be the environmental conditions and the dosage of aggregate, the concrete strength, the mixture proportioning, the use of special cements, the use of supplementary cementitious materials such as fly ash and the addition of fibres. Two other important factors are surface finish and curing conditions.[26]

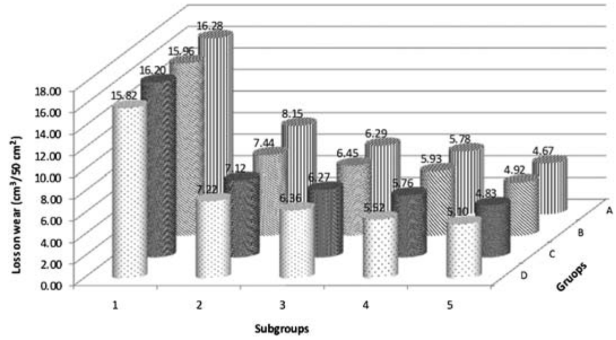
The results can be seen in Figs. 9–11. Mass loss graphics of concrete samples subjected to 440 cycles show that control concretes (A1, B1, C1 and D1) have the highest mass loss. Among them, the lowest mass loss is seen for D1. These results can be explained in terms of cement content. Compressive strength, which is very important for abrasion wear, as discussed above, increases with cement dosage. Thus, mass losses decrease, an effect which was reported before.[27]

As expected, mass losses increase with the applied load. As the abrasive particles achieve relative motion, shear forces are formed on the surface of the abraded material along with a normal load. While normal load helps abrasive particles penetrate into the specimen surface, shear force helps the formation of grooves and scratches on the surface. Thus, material transfer from the specimen surface occurs by a combination of normal load and shear forces.[28]

Several factors that affect the abrasion wear of concrete containing haematite need to be considered. First, there is an inverse proportionality between haematite volume and mass loss. This may be related to the hardness that haematite imparts to concrete; hardness is believed to be the most important factor that controls the wear of the aggregate in concrete. The hard aggregate should protect the softer paste, provided that there is an adequate aggregate/paste bonding strong enough to hold the aggregate securely in the face of the 'attacking' abrasion load.[11] Second, mass losses significantly decrease with increasing haematite content. This has to be related to a homogeneous distribution of haematite aggregates since concrete consists of a graded mix of aggregate particles in a cement paste. This in turn indicates that gradation of

Table 6 Mixture proportions

Group	Subgroup	Cement/ kg m^{-3}	Water/ kg m^{-3}	Superplasticiser/ 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}
A	1	300	117·0	3·0	528	524	1060	0	0
	2	300	117·0	3·0	449	445	901	246	253
	3	300	117·0	3·0	370	367	742	492	505
	4	300	117·0	3·0	290	288	583	738	758
	5	300	117·0	3·0	211	210	424	984	1010
B	1	350	136·5	3·5	504	500	1011	0	0
	2	350	136·5	3·5	428	425	859	235	241
	3	350	136·5	3·5	353	350	708	470	482
	4	350	136·5	3·5	277	275	556	705	723
	5	350	136·5	3·5	201	200	404	939	964
C	1	400	156·0	4·0	480	476	963	0	0
	2	400	156·0	4·0	408	401	819	224	230
	3	400	156·0	4·0	336	333	674	447	459
	4	400	156·0	4·0	264	262	530	671	689
	5	400	156·0	4·0	192	191	385	894	918
D	1	450	175·5	4·5	456	452	915	0	0
	2	450	175·5	4·5	387	384	777	212	218
	3	450	175·5	4·5	319	317	640	425	436
	4	450	175·5	4·5	251	249	503	637	654
	5	450	175·5	4·5	182	181	366	850	872



11 Mass loss of concretes under 15·0 kg load

aggregates and mixture and mixing process have been successful. Returning now to the microscopy results in Fig. 4*A*, a reasonably uniform distribution of the dispersed phase in the matrix was observed. Well dispersed (at approximately uniform distance from one another) haematite aggregates in the matrix prevent abrasive particles from penetrating more into concrete; thus, grading is important for decreasing mass losses.

Another factor at play is compressive strength. The addition of haematite, a material with higher density and higher hardness than cement, will increase the compressive strength. In addition, shrinkage of concrete goes down with increasing haematite content. Thus, shrinkage compensating concrete has a significantly increased abrasion resistance; fine cracks, which would facilitate the progress of abrasion, are absent.[29,30] The authors recall the molecular dynamic computer simulations of two-phase materials (matrix+reinforcement) showing crack formation and propagation leading to fracture.[31,32] There are also reports that the depth of wear tracks decreases with increasing compressive strength.[33,34]

The final factor is the relation between cement content and compressive strength. An increase in compressive strength is achieved by increasing the cement content and choice of low w/c.

The authors developed an equation for wear W that takes into account the key factors discussed above

Table 7 Volumes of aggregates in the mixtures/vol.-%

Groups	Subgroups	Haematite ratio	CSt-I	NRS	CSt-II	H_f	H_c
A	1	0	25·0	25·0	50·0	0·0	0·0
	2	15	21·3	21·3	42·5	7·5	7·5
	3	30	17·5	17·5	35·0	15·0	15·0
	4	45	13·8	13·8	27·5	22·5	22·5
	5	60	10·0	10·0	20·0	30·0	30·0
B	1	0	25·0	25·0	50·0	0·0	0·0
	2	15	21·3	21·3	42·5	7·5	7·5
	3	30	17·5	17·5	35·0	15·0	15·0
	4	45	13·8	13·8	27·5	22·5	22·5
	5	60	10·0	10·0	20·0	30·0	30·0
C	1	0	25·0	25·0	50·0	0·0	0·0
	2	15	21·3	21·3	42·5	7·5	7·5
	3	30	17·5	17·5	35·0	15·0	15·0
	4	45	13·8	13·8	27·5	22·5	22·5
	5	60	10·0	10·0	20·0	30·0	30·0
D	1	0	25·0	25·0	50·0	0·0	0·0
	2	15	21·3	21·3	42·5	7·5	7·5
	3	30	17·5	17·5	35·0	15·0	15·0
	4	45	13·8	13·8	27·5	22·5	22·5
	5	60	10·0	10·0	20·0	30·0	30·0

$$W = a_0 + a_1 w_{\text{cement}} + a_2 \sigma_{\text{compr}} + a_3 P_{\text{Load}} \quad (1)$$

where W is the wear loss (cm^3/50 cm^2), w_{cement} is the cement content (kg m^{-3}), σ_{compr} is the compressive strength (MPa), P_{Load} is the applied load (kg) and a_0 is a parameter.

The authors tested equation (1) against their available data (12 points). The resulting parameters are a_0=2·935, a_1=−0·0093, a_2=0·043 and a_4=0·958. These parameters provide virtually perfect fit to the experimental results. A perfect fit corresponds to the statistical parameter R^2=1. The authors have R^2=0·9997.

Conclusions

In this paper, the influences of metallic aggregate and cement content on the abrasive wear behaviour of concrete were investigated. Based on obtained test results, the following can be concluded.

The increase in cement content in the mixture increases the compressive strength. In addition, the replacement of limestone based aggregates in the mixture by haematite results in a concrete with a higher compressive strength. When these two aspects combine, they offer great potential for wear resistance. In other words, it is possible to greatly reduce the wear loss by reinforcing the composition with haematite particles, with increase strength substantially. The cement–haematite aggregate bond strength has been greatly improved. Still, concrete containing haematite resists abrasive wear more than PC even at high loads.

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