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Combined effects of fly ash and waste ferrochromium on properties of concrete

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ABSTRACT

Cement and water-to-binder ratio were kept constant as 400 kg/m^3 and 0.40, respectively. Cement was replaced with fly ash at the ratio of 10, 20 and 30 wt.%. Coarse limestone aggregates were replaced with coarse ferrochromium aggregate at the ratio of 25, 50 and 75 wt.%. On fresh concretes, slump, air content and unit weight tests were performed. On the hardened concretes, compressive strength, splitting tensile strength, elasticity modulus, abrasion resistance, freeze–thaw resistance, porosity and water absorption were determined. The use of fly ash lowers values several properties: compressive strength, splitting tensile strength, elasticity modulus and wear resistance; however freeze–thaw durability increases. Usage of ferrochromium aggregates increases strength of concrete and also abrasive wear resistance. Effect of ferrochromium aggregates on porosity and water absorption of concrete is insignificant while fly ash enhances these properties. A highly accurate equation relating compressive strength to splitting tensile strength is provided. An equation relating wear to compressive strength and fly ash volume fraction is also defined.

1. Introduction

The transformation from a conventional consumption based society to a sustainable society is important for several reasons such as lowering pollution of natural environment, prevention of exhaustion of natural resources and slowing down filling of final waste disposal facilities [1]. In this regard, one of the greatest challenges facing the concrete industry is to focus its objectives towards the achievement of sustainable development [2] since concrete is one of the principal materials for structures and it is widely used for many applications all over the world [3]. Thus, it is compelling to use life cycle and sustainable engineering approaches to concrete technology.

Waste and waste disposal has become a severe social and environmental problem. Unsalvaged fly ash, a by-product of coal power plants, causes environmental damage by causing air and water pollution on a large scale while the cost of storage of fly ash is very high [4]. In Turkey, the annual fly ash production is about 18 million tons which is more than the rest of all industrial wastes in the country [5]. In India, approximately 80 million tons of fly ash is generated each year [6]. The current annual production of fly ash worldwide is estimated around 600 million tons [7].

Slag is discarded as a waste material in large quantities during the ferrochrome production. Such slag is waste material obtained in the manufacture of high-carbon ferrochromium. The high-carbon FeCr metal with 65% Cr (minimum) content is produced in electric arc furnaces by a carbothermal process from the oxide of chromium ore with coke as the reducing agent at the temperature of about 1700 °C. Both the liquids of the high-carbon ferrochromium metal and of the slag flow out into ladles. After stratification of the metal from the slag by means of their different specific gravities, the molten slag – slowly cooling in the air – forms a stable crystalline dense rock product with mechanical properties similar to basalt [8]. It is classified as ferrous slag under iron-alloy slags. A relatively small percentage of this material finds application, but the vast majority of material generated each year is held in dumps; as land disposing costs increase, new disposal options are needed in [9].

Thus, very large amounts of waste are being produced around the world. The most common method of managing wastes is through their disposal in landfills – creating in that way huge deposits of wastes. In this situation, waste recycling alternatives are gaining increasing importance [10]. Also, in developed countries, restricted laws in a form of prohibitions or special taxes for creating waste areas have been implemented. Still stricter waste disposal regulations are expected in the future.

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Recycling has the potential to reduce the amount of wastes disposed of in landfills and to preserve natural resources. Recycling, one of the strategies in minimizing waste, offers three benefits: (i) reduces the demand for new resources; (ii) cuts down on transport and production energy costs; (iii) utilizes waste which would otherwise be gone into landfill sites. Concrete containing wastes can support construction sustainability and contribute to the development of the civil engineering area by using industrial waste, minimizing the consumption of natural resources and producing more efficient materials [11].

Recently, although ferrochrome slag has been tried in cement and in base layer material of road pavements [12], still its usage is very limited. Thus, in this study we investigated combined effect of fly ash and coarse ferrochrome slag as aggregate on the fresh, mechanical and some durability properties of concrete. We recall that mineral concretes are an alternative together with polymer based concretes [13].

2. Materials and methods

2.1. Aggregates

Since some 75–80 wt.% of concrete volume is comprised of aggregate, clearly the aggregate properties are important for the overall properties [14,15]. We produced plain concrete using the maximum 16 mm nominal size of crushed aggregate. The coarse aggregates were calcareous (mostly containing calcium carbonate) stone as crushed stone I (Cst-I) with the size 5–16 mm; and crushed stone II (Cst-II) with the size 9–16 mm. This aggregate is commonly used as a standard one in concrete and asphalt mixtures. The fine aggregate was natural sand with the size up to 4.75 mm. The aggregates were graded, washed and cleaned of clay and silts. Results of sieve analysis of fine and coarse aggregates used are presented in Table 1. Specific gravity and water absorption were determined according to ASTM C127 [16] standard. Sand had 3.0% water absorption value and its specific gravity was 2.67 g/cm^3. The water absorption values of the Cst-I and Cs-II were 0.9% and 0.9% and their specific gravities were 2.69 and 2.7 g/cm^3, respectively. Mixing ratios of sand, Cs-I and Cs-II were 55%, 20% and 25%, respectively.

Ferrochromium slag remains as a waste among others in the production of ferrochromium metal in the EtiKrom Works, Elazig, Turkey. The slag was prepared as aggregate by crushing and grinding it in a laboratory mill and then sorting it via sieves into two groups of coarse (>4.75 mm) and fine (<4.75 mm) aggregates. In this work coarse ferrochromium slag aggregates (see Fig. 1) were used. The specific gravity of slag is 3.17 g/cm^3. The chemical composition of the ferrochromium slag used is presented in Table 2. The slag consist mainly of SiO_2, Al_2O_3 and MgO in different phases such as spinel, $MgO{\cdot}Al_2O_3$, and forsterite, MgO·SiO2, but also smaller amounts of CaO, chromium and iron oxides and metal fragments [9]. The slag has a rough and porous surface; good adhesion to cement paste and good abrasion resistance were reported [12].

2.2. Cement

The cement used in all the concrete mixtures was Portland cement CEM II/A-M (P-LL) 42.5N. It complies with the requirement of the European Standard EN 197-1 [17]. Physical and mechanical properties and chemical analysis of the cement are presented in Tables 3 and 4, respectively.

2.3. Fly ash

Class F of fly ash (FA) was used; its chemical composition is listed in Table 5. The Blaine fineness, which is defined as a measure of the particle size or fineness of cement and supplementary cementitious materials, was 5.23×10^3 cm^2/g. The specific gravity was 2.1 g/cm^3. The cement paste in concrete is quite important since it is an agent to carry the aggregates.

Fig. 1. Ferrochromium slag aggregates.

Table 2
Chemical composition of the ferrochromium slag used.

Compound	Weight%
Cr_2O_3	5.17
Fe_2O_3	1.55
SiO_2	29.38
Al_2O_3	23.47
Na_2O	0.15
K_2O	0.06
MgO	38.5
CaO	0.93
LOI*	1.5

* Loss of ignition.

2.4. Superplasticizer

A superplasticizer (SP) 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 wt.%.

2.5. Mix proportions

Mix design was made in according with the absolute volume method. Binder content and water-binder ratio were kept constant as 400 kg/m^3 and 0.40, respectively. Coarse crushed limestone aggregate was replaced with waste ferrochromium slag aggregates at 25%, 50% and 75%. Cement was replaced with fly ash at 10%, 20% and 30% ratios. The dosage of superplasticizer was 1.0% of the binder content of concrete. It was assumed that approximately 1.5% air is trapped in fresh concrete. The concrete composition is given in Table 6.

2.6. Mixing, casting, curing and testing specimens

The concrete mixtures were prepared in a laboratory mixer with capacity of 60 dm^3. In a typical mixing procedure, the materials were placed in the mixer in the following sequence: first coarse aggregates and fine aggregates together, followed by cement, initially dry material mixed for 1 min, finally addition of 90% of water. After 1.5 min of mixing, the rest of the mixing water together with the SP was added.

After the mixing procedure was completed, slump tests were conducted on the fresh concrete to determine the workability (ASTM C143 [19]). Workability is essential for strength and durability after hardening. However, workability includes mixing, transporting, placing and segregation of freshly mixed concrete and there is no single test to evaluate workability. A widely used one is the so-called slump test.

Table 1
Aggregate gradations.

Aggregate codes	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
Sand	100.0	100.0	100.0	96.0	81.0	53.0	32.0	18.0	5.0	1.0
Cst-I	100.0	83.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cst-II	100.0	35.0	12.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0
Mixture	100.0	82.8	69.9	53.3	44.6	29.2	17.6	9.9	2.8	0.6

Table 3
Physical and mechanical properties of the 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)
2 Days	7 Days	28 Days	2 Days	7 Days	28 Days	2.25	3.15	1	3.15	$4.15 \cdot 10^3$
22.5	36.6	47.8	3.7	5.6	6.9					

Table 4
Chemical analysis of the Portland cement.

Compound	Total SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Cl	LOI*	Free CaO	Total admixture
Weight%	22.9	5.32	3.63	55.83	1.99	2.62	0	4.2	0.82	19.45

* Loss of ignition.

Table 5
Chemical composition of fly ash.

Chemical analysis	Class F fly ash (%)	ASTM C618 requirement (%) [18]
SiO_2	57.2	–
Al_2O_3	25.5	–
Fe_2O_3	6.01	–
$SiO_2 + Al_2O_3 + Fe_2O_3$	89.1	70.0 min
CaO	1.14	–
MgO	2.42	5.0 max
TiO_2	1.16	–
K_2O	4.6	–
Na_2O	0.42	1.5 max
SO_3	0.16	5.0 max
Cl	0.01	–
LOI*	1.12	6.0 max

* Loss of ignition (1000 °C).

The slump test, which is simple, quick and cheap, is almost universally used for nearly all types of medium and high workability concrete. It measures a flow property of concrete under self-weight after standard compaction. It is sensitive to small changes in water content [20].

From each concrete mixture, six specimens were cast in cylindrical molds of 150 mm diameter and 300 mm height. Three 150 mm cubes were cast. The cubes were used for the compressive strength test 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 demolding, the concrete specimens were immersed into lime saturated water until the testing time. Curing was done in accordance with ASTM C511 [21] standard. It is well recognized that adequate curing of concrete is very important not only to achieve the desired compressive strength but also to make durable concrete. After the curing process, all the specimens were stored in laboratory conditions at 20 ± 2 °C and 65% relative humidity (RH) for 24 h and tested at the end of that period.

The compressive strength tests were carried out in accordance with ASTM C39 [22] in 28 days. The splitting tensile strength tests were performed according to ASTM C496 [23] also after 28 days. Elasticity modulus was determined according to ASTM C469 [24] in 28 days. The same applies to the demolded unit weight test that was carried out according to ASTM C138 [25].

Cubic samples with the sizes 70 × 70 × 70 ± 1.5 mm (50.4 cm^2 cross-sectional area) were used for the determination of wear resistance in 28 days according to Turkish standard specifications TS699 [26]. TS699 is used as an alternative to ASTM C779 [27]. Other researchers have used this method and obtained reliable results [3,28–31]. According to TS699, the abrasion system has a steel disk with the diameter of 750 mm, a counter and a lever, applying a rotating speed of 30 ± 1 cycles/min. The abrasion testing apparatus is displayed in Fig. 2. Abrasion (20 ± 0.5 g) dust was spread on the disk, and the specimens were then placed there; load of 5.0 kg was applied to the specimens, and the disk was rotated for four periods, while a period was equal to 22 cycles. After that, the surfaces of the disk and the sample were cleaned. The procedure was repeated for each edge of the concrete samples (88 cycles total) by rotating the sample 90° in each period. The wear losses are calculated after 88 traversals over the same track (cm^3/cm^2). The abrasive dust used in this test was corundum (crystalline Al_2O_3).

3. Properties of fresh concrete

The results of unit weight, slump and air content values are presented in Table 7. The unit weights of concretes with fly ash are slightly lower than for concretes without fly ash in each group. As the fly ash content increases, the unit weight goes down. This is due to the difference of specific gravities of the fly ash and cement. By contrast, incorporating ferrochromium slag aggregate into the mixture increases the unit weight.

As the fly ash content increases, slump increases. Using concrete without fly ash as the reference, the changes caused by using fly ash are as follows: 9.7%, 25.8%, 35.5% for 10%, 20% and 30% FA. Approximately spherical fly ash particles provide ball bearing effects and reduce internal friction in fresh concrete and thus increase the flow

Table 6
Mixture proportions.

Mix code	FA (%)	FS (%)	FA (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)	Sand (kg/m^3)	Cst-I (kg/m^3)	Cst-II (kg/m^3)	FS (kg/m^3)
A1	0	0	0	400	160	4	1020	467	375	0
A2	0	25	0	400	160	4	1020	409	328	124
A3	0	50	0	400	160	4	1020	350	281	248
A4	0	75	0	400	160	4	1020	292	234	371
B1	10	0	40	360	160	4	1010	463	372	0
B2	10	25	40	360	160	4	1010	405	325	123
B3	10	50	40	360	160	4	1010	347	279	245
B4	10	75	40	360	160	4	1010	289	232	368
C1	20	0	80	320	160	4	1001	458	368	0
C2	20	25	80	320	160	4	1001	401	322	122
C3	20	50	80	320	160	4	1001	344	276	243
C4	20	75	80	320	160	4	1001	286	230	365
D1	30	0	120	280	160	4	992	454	365	0
D2	30	25	120	280	160	4	992	397	319	120
D3	30	50	120	280	160	4	992	341	273	241
D4	30	75	120	280	160	4	992	284	228	361

Fig. 2. Abrasive wear test apparatus.

ability and compaction of concrete [32,33]. Addition of ferrochromium slag slightly increases the slump, possibly because of higher density of the slag.

Air content values are in the desired range. Intentionally entrained air voids are bubbles typically 0.1 mm in diameter and are distributed evenly throughout the cement paste. Accidentally entrapped air usually forms much larger voids, often up to several millimeters in diameter. Differences between air content values determined should not exceed 1% to be able to accept concrete with uniformity [34]. And our findings were in line with this. Air content tends to increase with increasing of fly ash in the mixture.

4. Compressive strength of concretes

Relative compressive strengths are presented in Fig. 3. A response surface of compressive strength values depending on FA and FC is presented in Fig. 4.

The values decrease with an increase of fly ash contents, a significant effect. When compared with plain concrete (A1), the FA presence decreases the average compressive strength by 14.3%, 29.4%, 43.3% for 10%, 20% and 30% fly ash content, respectively. In the all concrete groups, significant reductions in compressive strength were observed with the addition of fly ash.

The compressive strengths of concretes with ferrochromium slag are slightly higher than without the slag in each group. There might be strong interfacial bonds between the ferrochromium aggregates and fly ash paste [8]. Rough surfaces of ferrochromium slag aggregate particles are filled with cement paste matrix. Therefore, ferrochromium slag aggregate provides greater bond strength due to the reaction of the glassy phase with cement past; this enhances the mechanical interlocking related to rough surfaces of the grains.

However, positive effects of ferrochromium presence are not strong enough to compensate the strength loss due to fly ash presence.

Table 7
Fresh concrete properties of concrete series.

Mix code	Unit weight (kg/m^3)	Slump (mm)	Air (%)
A1	2469	155	1.3
A2	2494	150	1.5
A3	2504	160	1.6
A4	2525	165	1.4
B1	2452	170	1.7
B2	2473	175	1.6
B3	2489	175	1.7
B4	2502	180	1.5
C1	2435	195	1.7
C2	2455	200	1.7
C3	2469	205	1.8
C4	2488	205	1.6
D1	2417	210	1.9
D2	2437	215	1.8
D3	2451	210	1.7
D4	2458	220	1.9

5. Splitting tensile strength

The results are presented in Fig. 5. The splitting tensile strength exhibits similar behavior as compressive strength. The presence of FA results in a decrease, the values vary between 3.7 MPa and 5.2 MPa. Fly ash decreases the splitting tensile strength of concrete 9.7%, 20.7%, 30.2% for 10%, 20% and 30% FA content, respectively. Even though these percentages seem high, the absolute values of reductions correspond to 0.5 MPa, 1.07 MPa and 1.56 MPa. Increasing ferrochromium aggregates in the mix increases splitting tensile strength of concrete. The reason of the increase in splitting tensile strength may be the existing strong interface bond, as previously mentioned, between paste and ferrochromium aggregates.

Usually, compressive strength is required in structural design; splitting tensile strength is also required in structural design for certain specific applications, such as structures in earthquake regions, airfield runways, pavement slabs and so on. A number of empirical relations between the compressive strength and splitting tensile strength have been proposed [35–44]. They can be summarized by the following general equation.

$$F_s = A(f_c)^B \quad (1)$$

where f_s is splitting tensile strength, typically in MPa; f_c is compressive strength also in MPa; A and B are adjustable parameters.

We have performed regression analysis using Eq. (1). The result is

$$f_S = 0.43(f_c)^{0.63} \quad (2)$$

Coefficient of determination R^2 for Eq. (2) is 0.99, indicating representation of the results within limits of experimental accuracy. Compared with other R^2 values shown in Fig. 6, Eq. (2) provides high reliability and accuracy.

The absolute relative errors (ARE) of estimated splitting tensile strength was used as another test of the accuracy of our Eq. (2). The ARE are defined as;

$$\mathrm{ARE}(\%) = \left|\frac{W_{\mathrm{Tested}} - W_{\mathrm{Estimated}}}{W_{\mathrm{Tested}}}\right| x100 \quad (3)$$

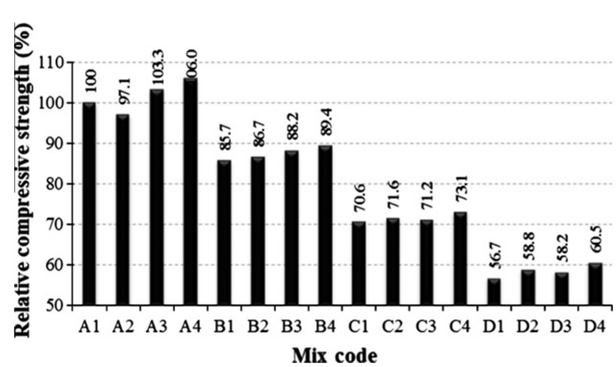

Fig. 3. Relative compressive strengths of the concretes.

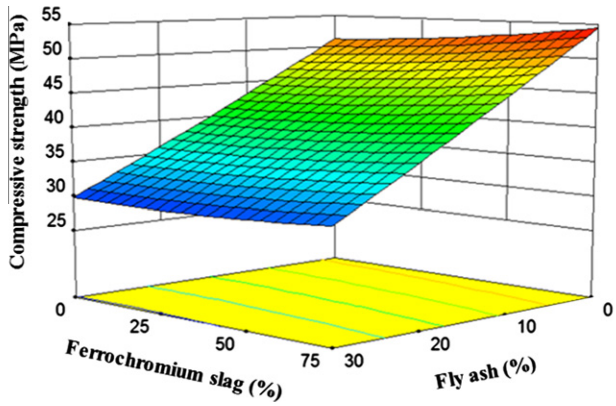

Fig. 4. Response surface of compressive strength depending on FA and FC.

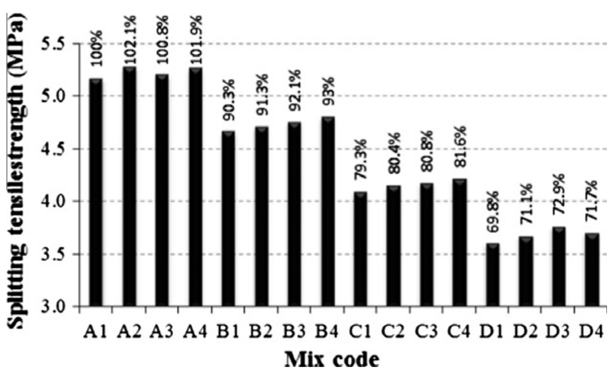

Fig. 5. Splitting tensile strengths of the concretes.

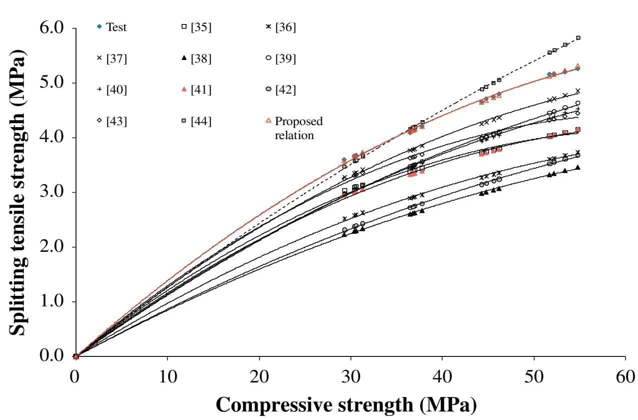

Fig. 6. Comparison between experimental data points and prediction curves of published and proposed empirical relations between splitting tensile strength and compressive strength of concrete.

The ARE values for Eq. (2) are presented in Fig. 7.

Moreover, the root mean square error (RMSE)

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(W_{\mathrm{Tested},\,j} - W_{\mathrm{Estimated},\,j})^2} \tag{4}$$

has also been calculated. Further, we also have the mean absolute relative error.

$$\mathrm{MARE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{W_{\mathrm{Tested}} - W_{\mathrm{Estimated}}}{W_{\mathrm{Tested}}}\right| \tag{5}$$

If the MARE is zero, this means that the model or prediction is perfect. The RMSE and MARE statistics are presented in Table 8.

6. Elasticity modulus

Elasticity modulus results are presented in Fig. 8. The values vary between 32.3 GPa and 36.9 GPa depending on fly ash and ferrochromium contents. The trends are similar as in the case of compressive strength – and for the same reasons.

Elastic compression modulus E_c is measured by recording the load–deformation curve. The testing procedure is much more complicated and time-consuming when compared to tests carried out to obtain the compressive strength f_c. Therefore, one has developed procedures [45] to calculate E_c from f_c such as

ACI 318 [35]

$$E_c = 4.73(f_c)^{1/2} \tag{6}$$

TS500 [46]

$$E_c = 3.25(f_c)^{1/2} + 14 \tag{7}$$

CEB90 [47]

$$E_c = 10(f_c + 8)^{1/3} \tag{8}$$

NS 3473 [48]

$$E_c = 9.5(f_c)^{0.3} \tag{9}$$

Comparison of experimental (called "test") and calculated values is presented in Fig. 9.

7. Wear resistance

Wear resistance results are presented in Fig. 10 in the form of mass losses.

As seen from Fig. 10, mass loss increases with increasing fly ash content in the mixture. It is believed that mass loss and the compressive strength are approximately inversely proportional [49–53]. We recall in this context the compressive strength results.

Concretes containing ferrochromium aggregates have more resistance to abrasive wear. This may be related to the specific gravity of ferrochromium slag and its chemical composition with high wear resistant compounds such as Al_2O_3, SiO_2, Fe_2O_3 and Cr_2O_3. The presence of ferrochromium aggregate with its high surface area results in less wear on the surface. The paste is softer and weaker, thus it has lower wear resistance than ferrochromium aggregate.

We see from the above Figure that the relationship is not linear, it is rather concave. Relationship between wear and compressive strength was presented in Fig. 11.

In Fig. 12 we compare the wear losses to those of concrete A1 (without FA and ferrochrome).

As seen from Fig. 12, concretes without fly ash have high resistance to wear. Mass losses are 13.7%, 26.6%, 32.6% for 10%, 20% and 30% fly ash, respectively. Ferrochromium aggregates compensate effects due to fly ash presence on mass loss.

For the estimation of the wear (W) of concrete depending on both compressive strength (f_c) and fly ash volume fraction (V_{FA}), experimental data were fitted to a polynomial type of mathematical model by using analysis of variance (ANOVA). The fitted regression models are given below:

$$W = -319.85 + 15.06f_c + 9.21V_{FA} - 0.17f_c^2 - 0.17V_{FA}^2 - 0.21f_cV_{FA} \tag{10}$$

The correlation coefficient (R^2) of the model was 0.82. Fig. 13 illustrates the actual values versus predicted ones. Deviations from the line seem random and thus reflect the experimental accuracy.

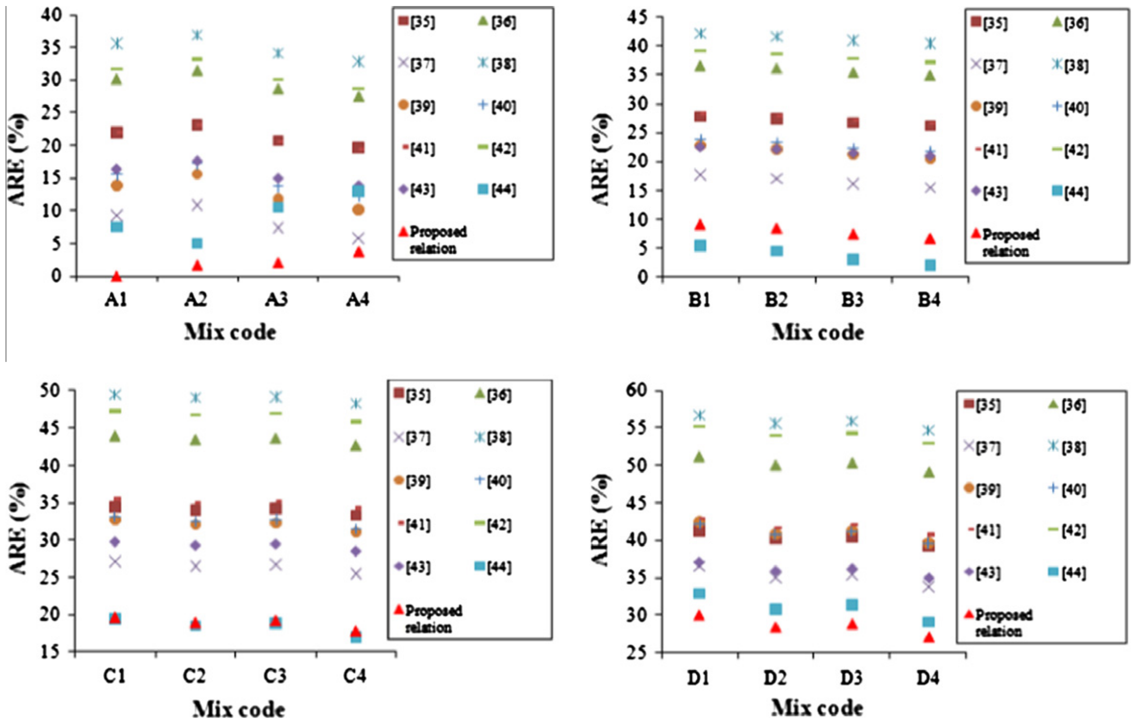

Fig. 7. Comparison of the ARE statistics.

Table 8
The RMSE and MARE statistics (%).

	[35]	[36]	[37]	[38]	[39]	[40]	[41]	[42]	[43]	[44]	Proposed relation
MARE	0.31	0.40	0.22	0.45	0.27	0.28	0.31	0.43	0.26	0.16	0.14
RMSE	1.63	2.09	1.24	2.37	1.49	1.52	1.67	2.24	1.38	0.97	0.91

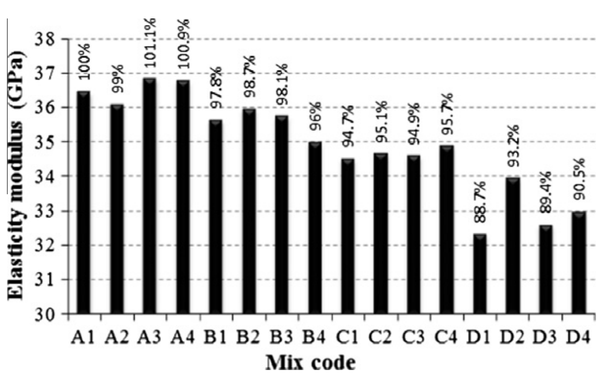

Fig. 8. Elasticity modulus of concretes.

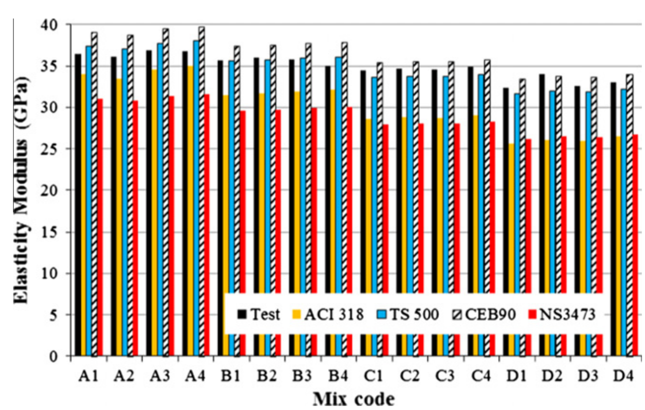

Fig. 9. Comparison of elasticity modulus derived from codes.

8. Freeze–thaw durability, porosity and water absorption

The results of freeze–thaw durability tests are presented in Fig. 14. Also relative reduction of compressive strength on the bars is shown in Fig. 14. We see in Fig. 14 that all concrete types loss strength in cycling. There is no significant effect of ferrochromium aggregates on the freeze–thaw durability of concrete. However, increment in fly ash content in concrete significantly decreases the effect of FT cycles. We see that strength loss of concrete without fly ash is around 15%. The values are around 11%, 8% and 5% for 10%, 20% and 30% fly ash content, respectively.

Micro-cracks mainly exist at cement paste-aggregate interfaces within concrete even prior to any loading and environmental effects. When the number of freeze–thaw (FT) cycles increases, the degree of saturation in pore structures increases by sucking in water near the concrete surface during the thawing process at temperatures above 0 °C. Some of the pore structures are filled fully with water. Below the freezing point of those pores, the volume increase on freezing causes tension in the surrounding concrete. If the tensile stress exceeds the tensile strength of concrete, micro-cracks occur. By continuing FT cycles, more water can penetrate the existing cracks during thawing, causing higher expansion and still more cracks during freezing. The load carrying area will decrease with the initiation and growth of every new crack. Necessarily the compressive strength will decrease with

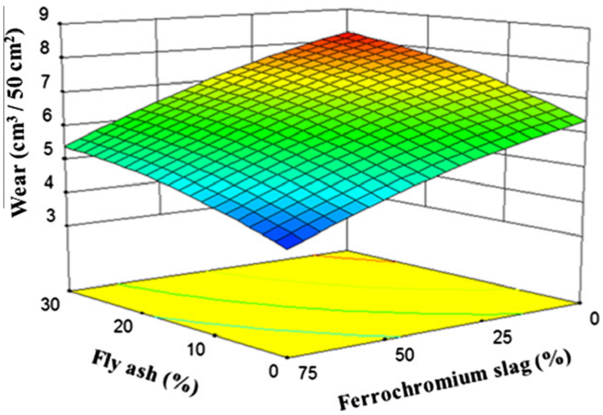

Fig. 10. Response surface of mass loss depending on FA and FC.

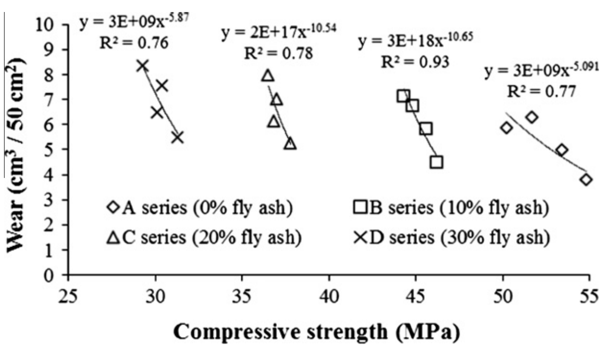

Fig. 11. Relationship between wear and compressive strength.

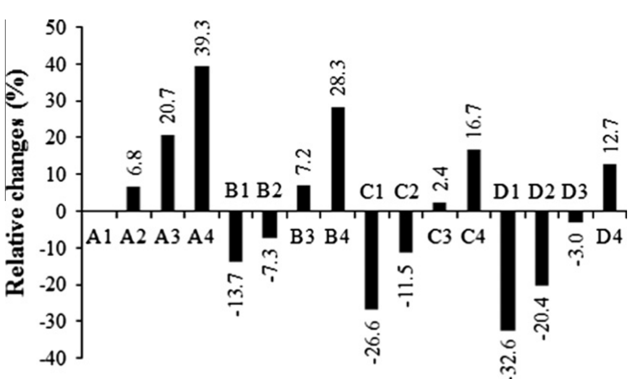

Fig. 12. Relative mass loss changes of concretes compared to A1.

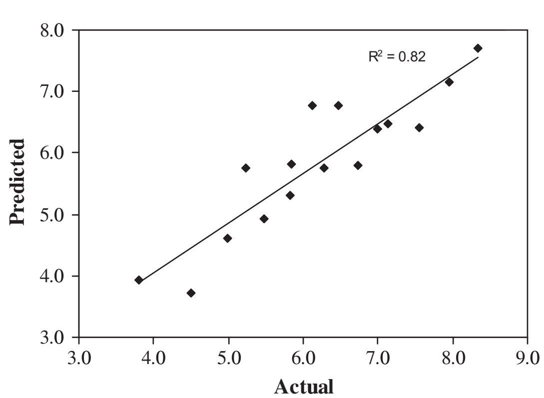

Fig. 13. Actual value versus predicted value by model for the wear.

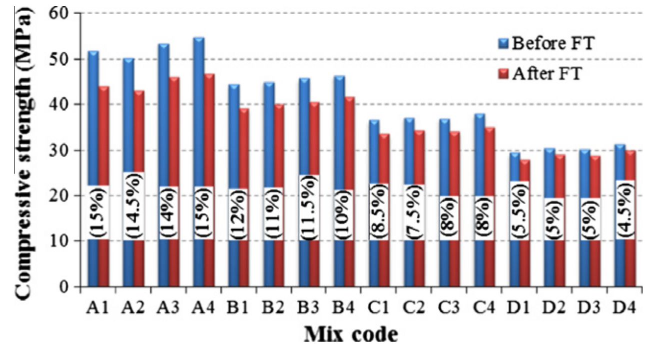

Fig. 14. Freeze–thaw durability of concretes.

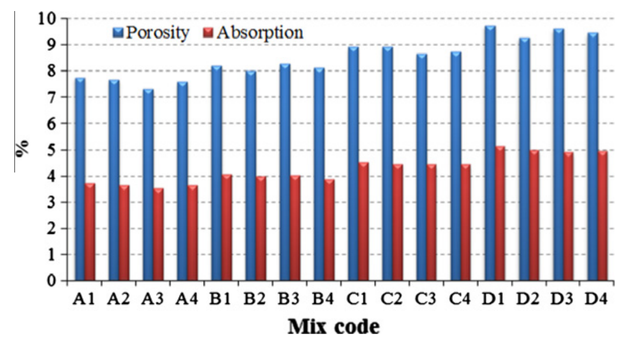

Fig. 15. Porosity and water absorption values of concretes.

the number of FT cycles [21,54]. Fly ash is also quite effective in producing concrete with low permeability [55,56]. Thus, concrete sucks less water – causing less expansion in case of freezing as mentioned above. This may increase freeze thaw durability of concrete. Considering all our results, fly ash concretes have appropriate air content and improve the microstructure in 28 days or longer curing – providing good resistance against effects of freeze thaw cycles.

Porosity and water absorption values of the concretes are presented in Fig. 15.

As shown in Fig. 15, the use of ferrochromium aggregates and fly ash replacing by limestone aggregates and cement, respectively, show no considerable effect on both porosity and water absorption of concrete. We see a little change on porosity and water absorption depending on volume fraction of fly ash and ferrochromium aggregate.

Inclusion of fly ash does affect porosity and water absorption of concrete. Porosity and water absorption values increase with the increase of fly ash content. Average porosities of concrete series are 7.5%, 8.2%, 8.8% and 9.5% for 0%, 10%, 20% and 30% fly ash, respectively. Average water absorption values of concrete series are 3.6%, 4.0%, 4.5% and 5.0% for 0%, 10%, 20% and 30% fly ash content, respectively. The porosity decreases paralleling the water absorption.

Poon et al. [57] noted that replacing cement by fly ash increases the porosity and reduces the pore diameter of cement paste. This may act as air-entraining agent, and thus reduces the effect of freeze thaw action.

9. Conclusions

The civil engineering construction industry seems capable of absorbing large amounts of waste – incorporating the waste into useful products. This is an example of a more general tenet of industrial ecology for a sustainable future of the world: industry by-products can be used as raw materials in other industries. Fly ash increases workability and air content of concrete while decreasing unit weight of concrete. Incorporating coarse ferrochromium aggregate into concrete slightly increase unit weight and slump values of concrete. Compressive strength of concrete significantly decreases with increasing use of fly ash in the mixture. Ferrochromium aggregates slightly increase the compressive strength. Splitting tensile strength of concrete decreases with increasing fly ash concentration while it increases by addition of ferrochromium. There is a well obeyed quantitative relationship between compressive strength and splitting tensile strength. Elastic modulus of concrete decreases with increasing fly ash content. Influence of ferrochromium aggregates on elasticity modulus is insignificant. Wear resistance of concrete significantly increases with the increase in contents of ferrochromium aggregates while fly ash reduces the wear resistance. There is a relationship between the wear resistance and its compressive strength, namely mass loss decreases as the compressive strength increases. Freeze–thaw resistance is enhanced by ferrochromium aggregates when compared to concrete without the aggregates. The positive effect is significantly larger for fly ash. Porosity and water absorption increase with increase of fly ash content. Effects of ferrochromium aggregates on these properties are negligible.

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