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Durability characteristics of copper slag concrete with fly ash

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Professional paper

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Durability characteristics of copper slag concrete with fly ash

The durability of the combination of Fly Ash (FA) and Copper Slag (CS) in concrete is studied in the paper. Experimental study was conducted to determine durability properties such as saturated water absorption, porosity, coefficient of water absorption, sorptivity, rapid chloride ion penetration test, and Alkalinity (pH) test. The microstructure of concrete was tested and quantitative analysis was carried out at the age of 90 days by the scanning electron microscope and energy dispersive X-ray. The results show that concrete properties are improved by the combined use of FA and CS.

Key words:
copper slag concrete, flay ash, water absorption, porosity, chloride ion penetration

Stručni rad

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Karakteristike trajnosti betona s bakrenom zgurom i s dodatkom letećeg pepela

U radu se razmatra trajnost kombinacije letećeg pepela (FA) i bakrene zgure (CS) u betonu. Provedeno je eksperimentalno istraživanje o pokazateljima trajnosti kao što su upijanje vode do zasićenja, poroznost, koeficijent upijanja vode, sorptivnost, brzi pokus prodiranja kloridovih iona te pokus alkalnosti (pH). Ispitana je i mikrostruktura betona te je obavljena kvantitativna analiza nakon 90 dana pomoću pretražnog elektronskog mikroskopa i energijski razlučujuće rendgenske spektrometrije. Dobiveni rezultati pokazuju da se primjenom kombinacije FA i CS poboljšavaju svojstva betona.

Ključne riječi:
beton s bakrenom zgurom, leteći pepeo, upijanje vode, poroznost, prodiranje kloridovih iona

Fachbericht

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Merkmale der Beständigkeit von Beton mit Kupferschlacke und Flugasche

In der Arbeit wird die Beständigkeit der Kombination von Flugasche (FA) und Kupferschlacke (CS) im Beton untersucht. Es wurde eine experimentelle Untersuchung der Parameter wie Wasseraufnahme bis zur Sättigung, Porosität, Koeffizient der Wasseraufnahme, Sorptivität, Schnelltest der Eindringung von Chloridionen und ein Alkalinitätstest (pH) durchgeführt. Es wurde die Mikrostruktur des Betons geprüft und eine quantitative Auswertung nach 90 Tagen anhand eines Elektronenmikroskops und einer energieauflösenden Röntgenspektrometrie durchgeführt.

Schlüsselwörter:
Beton mit Kupferschlacke, Flugasche, Wasseraufnahme, Porosität, Eindringung von Chloridionen

1. Introduction

Every concrete structure should continue to perform its intended functions to the required strength and serviceability levels during the specified or traditionally expected service life. Moreover, concrete used in such structures must be able to withstand the processes of deterioration to which it is expected to be exposed. Such concrete is said to be durable [1]. Concrete has been the most significant building material for many generations. Concrete structures are built in highly polluted urban and industrial areas, aggressive marine environments, harmful subsoil water, coastal areas, and in many other hostile environments. Large sums of money are being spent on concrete repair and maintenance and, as a result, concrete must be able to withstand various deterioration processes.

When excess water in concrete evaporates, it leaves voids inside the concrete element by creating capillaries that are directly related to the concrete porosity and permeability. Hydration products consist of C-S-H gel, ettringite crystals, and mono-sulphate, and of related gel pores, capillary pores, and entrapped and entrained air voids. These are the factors that cause porosity of concrete. The volume of moisture that may pass through concrete depends on its permeability. The permeability of cement paste also varies with the age of concrete or with the degree of hydration. Almost impervious concrete can be obtained by proper selection of ingredients, mix proportioning, and following good construction practices [2]. Although compressive strength is to a great extent a measure of durability, it is not entirely true that strong aggregate is always needed for a durable concrete [3]. So, the durability of concrete depends on environmental conditions and also on the movement of water and gas through concrete. Good particle packing density of concrete prevents solely the penetration of water and other chemicals.

The durability of concrete is mostly affected by three factors: water that carries pure or aggressive ions, carbon dioxide, and oxygen. They can move through concrete in different ways, but all transports depend primarily on the structure of the hydrated cement paste. The movement of various fluids through concrete takes place not only by flow through the porous system, but also by diffusion and sorption. Hence, the main concern is really the penetrability of concrete [4].

The sorptivity or capillary suction is the transport of liquids in porous solid due to surface tension, acting on capillaries, viscosity, density, surface tension of the liquid, and pore structure [5]. Concrete is a strong and tough material but it is porous and so it interacts with the exposed environment. The sorptivity of concrete is a quantity that measures the unsaturated flow of fluids in concrete [6].

The application of flay ash (FA) in concrete mixture improves durability properties because it ensures lower permeability and an improved microstructure of concrete [3]. As a result, FA concrete not only improves properties of concrete, but it also helps in preventing environmental pollution. Various studies have been made with regard to the use of FA for cement, and copper slag as a substitute for fine aggregate. Concrete with 25 % of FA content as a cement replacement material showed lowest value of saturated water absorption, sorptivity, and chloride diffusion compared to values obtained at control concrete mixes. The porosity increases with an increase in FA replacement level and decreases with an increase in its fineness. In previous studies, it is reported that the inclusion of FA reduces the sorptivity and chloride ion permeation significantly at 28 days, and that these values reduce even further at 6 months. [7-9].

Concrete with 40 % of copper slag (CS) as sand substitute can achieve higher strength compared to the control concrete [10, 11]. The durability characteristics such as water absorption and permeability decrease continuously with an increase in copper slag content [12]. However, not many durability studies have been made with regard to FA and copper slag (CS) incorporated in concrete. Thus, this experimental study focuses on transport properties of concrete containing FA and CS. Furthermore, microstructural studies and quantitative analysis are conducted by SEM (*Scanning Electron Microscope*) and EDAX (*Energy Dispersive X-ray analysis*), respectively. Preliminary compressive strength testing is conducted on cubes at 7, 28, 56, and 90 days. The concrete strength increases in proportion with an increase in curing period. At 90 days, the strength varies from 43.22 N/mm^2 to 59.11 N/mm^2. In addition, CS used as replacement for fine aggregate in the proportion of up to 100 % behaves better when compared to control concrete.

2. Experimental study

2.1. Materials

The Chettinad Ordinary Portland Cement (OPC), i.e. a 43 grade cement compliant with IS8112 (part1), 2013 [13], was used in the experimental investigation. Its basic properties were evaluated, as shown in Table 1. The low calcium fly ash (class F) obtained from Thermal Power Plant, Salem (Tamil Nadu), India, compliant with IS3812 (part1), 2003 [14], was used. The specific gravity of fly ash was 2.18. The fine aggregate was first sieved through 4.75 mm sieve to remove the particles greater than 4.75 mm. Crushed blue granite stone of maximum size 20 mm was used as coarse aggregate. The copper slag used in this paper was obtained from Sterlite Industries India Limited (SIIL), Tuticorin and Tamil Nadu.

Table 1. Properties of cement (OPC 43 grade) and mortar

Cement	Specific gravity	3,05
	Standard consistency [%]	36
	Initial setting time [min]	95
	Final setting time [min]	420
Mortar	Mortar compressive strength after 7 days [N/mm^2]	21.06
	Mortar compressive strength after 28 days [N/mm^2]	26.08

The properties of fine aggregate, CS and coarse aggregate are given in Table 2 [15]. Specific gravity and density of CS amount to 3.52 and 1750 kg/m^3, respectively. These qualities show that the density of CS is in contrast to that of the fine aggregate. Similarly, CS has higher fineness modulus (3.68). It could be inferred from the results that the CS is coarser than the fine aggregate. Furthermore, gradation tests were conducted for fine aggregate, CS, and coarse aggregate. The gradation curves are presented in Figure 1. Potable water is generally considered for concreting purposes. Thus, locally available potable water was used for mixing and curing.

Table2. Properties of fine and coarse aggregate

Agregate Property	River sand	Copper slag	Coarse aggregate
Specific gravity	2.5	3.52	2.7
Fineness modulus	2.74	3.68	7.61
Bulk density [kg/m^3]	1420	1750	1380
Void ratio	0.77	0.8	0.95
Grading zone	II	-	Max. size 20 mm

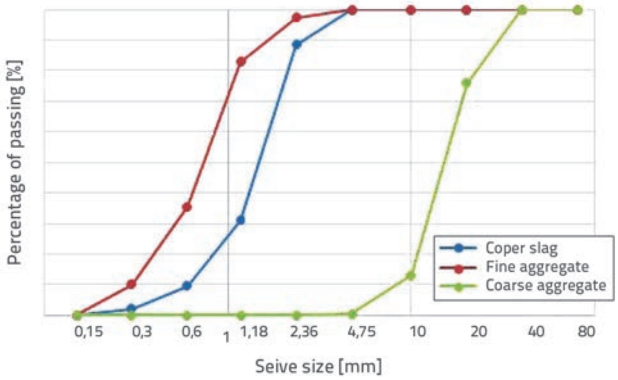


Figure 1. Particle size distribution for copper slag, fine aggregate and coarse aggregate

2.2. Mix design proportions

The concrete mixture is compliant with IS 10262-2009 [16] and its proportions are given in Table 3. C25/30 grade concrete was used in this research. In the designation of concrete mix, M30 was used, refers to the mix and the number to the specified compressive strength of 150 mm size cube at 28 days, expressed in N/mm^2. The cement and water cement ratio were kept constant as 380 kg/m^3 and 0.4, respectively. Twenty four mix proportions were prepared. The cement was partially replaced by FA from 0 % to 30 % with 10 % increments by mass, while fine aggregate was replaced by CS from 0 % to 100 %, with 20 % increments by volume.

2.3. Preparation of test specimens

The concrete was mixed in the laboratory tilting drum mixer machine. Concrete cubes 100 mm x 100 mm x 100 mm were cast so as to determine the saturated water absorption, porosity, coefficient of water absorption, and sorptivity. The samples were demoulded after 24 h and then cured under water up to 90 days. Standard cylindrical specimens 100 mm diameter and 50 mm length were cast for the chloride ion penetration test. These specimens were stripped after 24 h and cured with distilled water up to 90 days. Powdered samples for the alkalinity test were taken from specimens after 90 days of curing.

3. Experimental tests

The durability of concrete depends on environmental conditions and on the movement of water and gas entering and moving through concrete. Concrete containing supplementary cementitious materials such as FA required 56-90 days curing period in order to develop potential properties. The main objective of the present investigation was to study the microstructure related properties such as the Saturated Water Absorption (SWA), porosity, coefficient of absorption, sorptivity and chloride ion penetration, and pH values.

3.1. Saturated water absorption (SWA)

The SWA test was conducted in accordance with the ASTM C1642-13 [17]. After 90 days of curing period, the specimen was oven dried at 110 °C for no less than 24 hours, as shown in Figure 2.

Figure 2. Concrete cubes in oven

Table 3. The composition of the concrete mixtures used in the test (designation M30)

Specified compression strength [N/mm^2]	Cement [kg/m^3]	Fine aggregate [kg/m^3]	Coarse aggregate [kg/m^3]	Water [kg/m^3]	w/c ratio
30	380	596	1281	152	0.4

After removal of each specimen from the oven, it was allowed to cool in dry air to determine the mass. When two consecutive mass values closely agreed, the specimen was considered dry. Then the concrete specimens were immersed in water until the constant mass was obtained. Soaking after immersion in [%] is given by the expression (1):

$$[(B-A)/A] \times 100 \quad [\%] \qquad (1)$$

where:
A - mass of oven dried sample in air, [g]
B - mass of surface dry sample in air after immersion, [g].

3.2. Porosity

Porosity is a measure of the proportion of pores in the total volume of concrete, and it is usually expressed in percentage. For the determination of porosity, the formula given with the expression (2) is used:

$$[(A-B)/V] \times 100 \quad [\%] \qquad (2)$$

where:
A - mass of oven dried sample in air, [g]
B - mass of surface dry sample in air after immersion, [g]
V - volume of sample.

The volume of voids is represented by the volume of water lost on oven drying at 105 °C to constant mass.

3.3. Sorptivity test

The sorptivity was determined according to ASTM C1585-13 [18] at the age of 90 days. This test method is used to determine the rate of absorption (sorptivity) of water by measuring the increase in the mass of a specimen resulting from absorption of water as a function of time, when only one surface of the specimen is exposed to water. The exposed surface of the specimen is immersed in water and water ingress of unsaturated concrete is dominated by capillary suction during initial contact with water. The test determines the rate of capillary-rise absorption by a concrete 100mm cube which rests on small supports in a manner such that only lowest 2 to 5mm of the cube is submerged. It is shown in Figure 3.

Figure 3. Sorptivity test

The increase in the mass of cube over time is recorded:

$$i = St^{0.5} \qquad (3)$$

where:
i - increase in mass in g/mm^2 (mass increases due to the ingress of water, 1 g is equivalent to 1 mm^3, so it can be expressed in mm)
t - time, measured in minutes, and at which the mass is determined
S - sorptivity in mm/min$^{0.5}$.

The quantity of water penetrated per unit surface area exposure to water is plotted against the square root of time of exposure. The test data generally fell on a straight line passing through the origin. The slope of this straight line is considered as a measure of the velocity of movement of water through capillary pores and is called sorptivity.

3.4. Coefficient of absorption

It is calculated from expression (4), according [19]:

$$ka = (Q/A)^2 \times (1/t) \qquad (4)$$

where:
Q - quantity of water absorbed by the oven dried specimen over time t = 60 minutes
A - total surface area of concrete specimen affected by penetration of water.

Lower value of ka indicates higher degree of imperviousness of concrete for water penetration.

3.5. Rapid chloride ion penetration test

The chloride permeability is measured in accordance with ASTM C1202-12 [20] at the age of 90 days. This test method consists of monitoring the amount of electrical current passed through 50 mm thick and 100mm nominal diameter disc during a 6-hour period. A potential difference of 60V direct current is maintained across the end of the specimen. One side of the cell is immersed in a 3 % (NaCl) sodium chloride solution and is connected with the negative terminal of power supply. The other side of the cell is filled with 0.3N (NaOH) sodium hydroxide solution and connected with positive terminal of the power supply. It is depicted in Figure 4.

Figure 4. Rapid chloride ion penetration test

Table 4. Results of durability properties and alkalinity test

Combination of Fly Ash (FA) and Copper Slag (CS) in concrete		Saturated water absorption	Porosity [%]	Coefficient of absorption In x 10^{-14} [mm/s]	Sorptivity x 10^{-4} [mm/min$^{-0.5}$]	Rapid chloride penetration test [C]	pH value
FA0	CS50	4.1	11	1.15	1	112.5	12.5
FA0	CS20	3.6	9	0.42	1	300.7	11
FA0	CS40	3.8	10	1.15	2	200.5	11.3
FA0	CS60	3.5	8.5	1.67	1	580	11.3
FA0	CS80	3.3	8	2.26	1	197.1	11.5
FA0	CS100	3	8	0.74	0.6	249.3	11.6
FA10	CS50	4.2	11	0.42	1	200.7	11
FA10	CS20	3.9	10	0.42	1	378.9	11.1
FA10	CS40	4.2	11	0.74	2	200.7	11.1
FA10	CS60	3.7	10	0.74	1	801.9	11.1
FA10	CS80	3.2	9	0.42	1	102.6	11.1
FA10	CS100	2.4	7	0.42	1	194.4	11.1
FA20	CS50	4	10	0.74	1	264.6	10.5
FA20	CS20	3.6	9	0.74	2	128.7	10.6
FA20	CS40	3.8	10	0.42	2	261.9	10.5
FA20	CS60	3.3	9	0.18	1	587.7	10.5
FA20	CS80	3.2	9	0.42	1	283.5	10.7
FA20	CS100	2.8	8	0.42	1	195.3	10.8
FA30	CS50	4.6	11	0.42	1	267.3	10.2
FA30	CS20	4.2	11	0.74	2	184.5	10.8
FA30	CS40	5.6	14	0.74	2	151.2	10.9
FA30	CS60	4.2	12	0.42	2	302.4	11
FA30	CS80	3.2	9	0.42	1	101.7	11.7
FA30	CS100	3.2	9	0.42	1	249.3	10.5

Fly ash (FA) and copper slag (CS) in the mixture, for example: FA10 (10% of fly ash), CS20 (20% of copper slag)

The total charge passed, in coulombs, was found to be related to the resistance of the specimen to chloride ion penetration.

$$Q = 900(I_0 + 2I_{30} + 2I_{60} + \ldots\ldots\ldots\ 2I_{300} + 2I_{330} + I_{360}) \qquad (5)$$

where:

Q - charge passed (coulombs)
I_0 - current (amperes) immediately after voltage is applied
I_t - current (amperes) at t min after voltage is applied

Figure 5. Alkalinity test

3.6. Alkalinity test

Ten gram crushed samples were taken from twenty-four mix proportions at the age of 90 days and mixed with 50 ml distilled water. The mixture was completely stirred. The solution was kept for 72 hours and then pH meter was immersed into the solution. The structure is shown in Figure 5. The pH values of the solution are presented in Table 4.

4. Results and discussion

After 90 days of water curing, specimens were tested to determine durability properties such as the SWA, porosity, coefficient of absorption, sorptivity and chloride ion penetration by Rapid Chloride Penetration Test (RCPT). The Alkalinity (pH) test was also conducted. The results are given in Table 4.

Saturated water absorption, Porosity and Coefficient of water absorption

The SWA and porosity values are presented in Figure 6. These values are higher, when concrete does not contain CS. Therefore, the filling effect of concrete is reduced if CS is not added and, hence, the pore diameter of the cement paste is increased. The SWA and porosity values increase when concrete with 40 % of CS is replaced by sand. Furthermore, the values decrease continuously when 100 % sand replacement with CS is reached. When natural sand is replaced by 100 % of CS, the SWA values amount to 3 %, 2.4 %, 2.8 % and 3.2 % for 0 %, 10 %, 20 %, and 30 % of FA, respectively. The values show that they are by 27 %, 41 %, 32 % and 22 % smaller compared to the control concrete. Moreover, average concrete porosity values are 8 %, 7 %, 8 %, and 9 % for 0 %, 10 %, 20 % and 30 % of FA, respectively. When compared to the control concrete, these values are lower by 27 %, 36 %, 36 % and 18 %, respectively. Generally, the SWA and porosity decrease when sand is replaced by 80 % and 100 % of CS and cement is replaced by 0-30 % of FA. These experimental results show that the concrete water absorption rate increases linearly with the porosity of concrete.

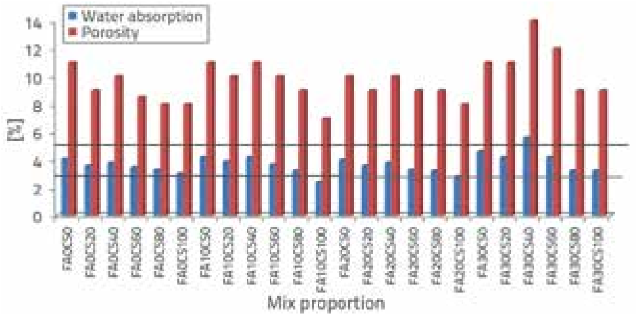


Figure 6. Water absorption and porosity

According to [7], if the value of SWA is below 3 %, it is considered to be a "good" concrete. If the SWA ranges from 3 % to 5 % it is considered as an "average" concrete and, above 5 %, it is classified as a "poor" concrete. In this paper, the values of SWA are 2.4 % and 2.8 % for FA10CS80 and FA20CS80, respectively. Hence, this concrete may be considered as a good concrete. All other mix proportions except FA30CS40 are classified as average. This shows an insufficiency of gel pores due to hydration, and so capillary pores are interconnected. Even complete hydration would not produce enough gel to block all the capillaries. The higher SWA represents more pores and greater movement of water and, hence, a higher degree of volume changes.

A regression analysis (curve fitting techniques) was conducted in order to estimate the effect of the CS and FA on the SWA and porosity. A good correlation between the SWA and porosity was established, as shown in Figure 7. The exponential equation is well fitted with experimental data. The correlation index or the coefficient of determination (R^2) varies from 0.76 to 0.93. It expresses the proportion of variance in the dependent variable like porosity explained by an independent variable such as water absorption. It can therefore be stated that an economical and low absorption concrete depends on the selection of appropriate quantities of cement, FA and CS.

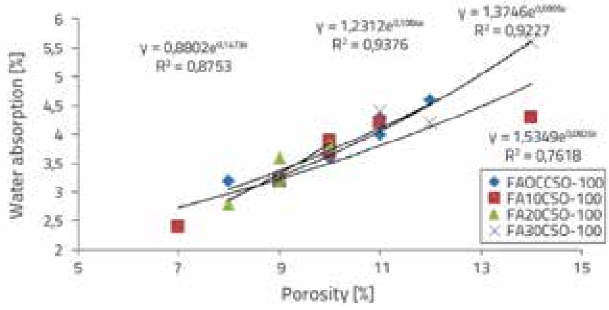
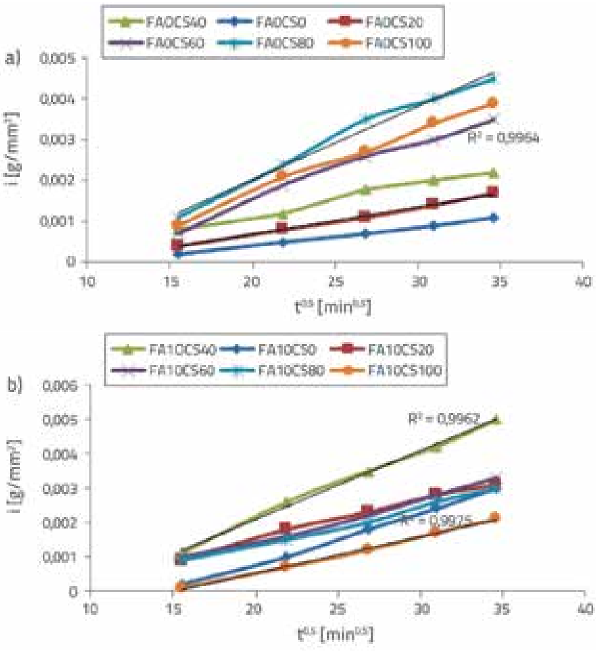


Figure 7. Variation of SWA with porosity

The coefficient of water absorption of concrete falls from 0.18 x 10^{-14} mm/s to 2.26 x 10^{-14} mm/s when cement is replaced by 0 % FA and sand is replaced by 80 % of CS, the highest value being 2.26 x 10^{-14}mm/s. This is by 96 % higher compared to the control concrete, whereas the coefficient of water absorption is less for concrete with the CS and FA combination. The above combination ensures a good particle packing density. Moreover, a hydration product such as the surplus $Ca(OH)_2$ is consumed by FA and gives an additional C-S-H gel to the concrete. So, the solid content of the paste increases with an increase in the duration of hydration and, hence, the dense paste is created in the mature state. The capillaries are blocked by gel and segmented. Hence, they turn into capillary pores and are filled by gel pores. Consequently, the capillary pores are disconnected and, as a result, penetration of water through pores is reduced. On the other hand, capillary pores decrease with the progress of hydration.

Sorptivity

Sorptivity is the rate of unidirectional movement of water through capillary suction. For all mix proportions, sorptivity values range from 0.6 x 10^{-4} to 2 x 10^{-4} mm/ (min) $^{0.5}$. Lower values are preferable. These values indicate that water penetrates at a very slow rate. In addition, it can be seen from the results that FA0CS100 concrete exhibits greater resistance to water absorption by capillary suction than the concrete containing FA and CS. Typical plots of cumulative water absorption against the square root of time are shown in Figure 8 for all the twenty-four concrete mix proportions tested.



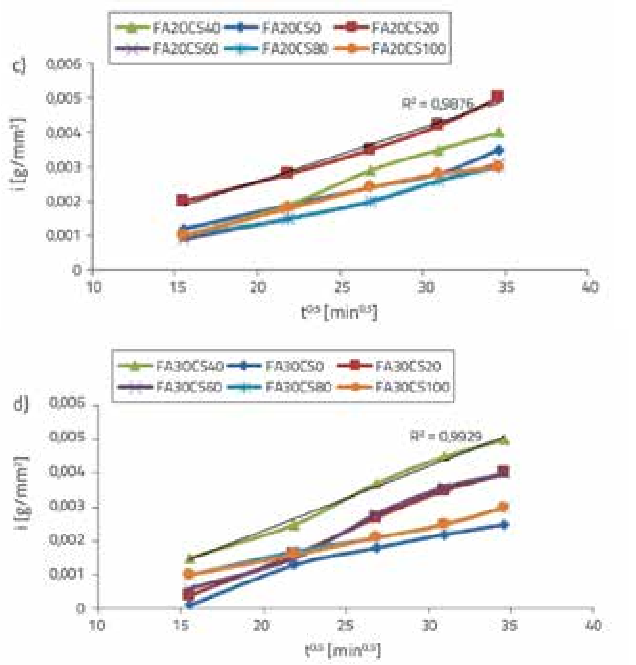


Figure 8. Cumulative water absorption for concrete containing FA and CS

This duration has produced linear relationships (least squares fitting) which give correlation index of the coefficient of determination (R^2) greater than 0.99. Water absorption of a concrete surface depends on many factors including concrete mix proportions, supplementary cementitious materials, duration of curing, and degree of hydration or age.

Chloride penetration

This test is conducted for all mix proportions for the time of up to six hours. The results are presented in Figure 9. These results are compared with ASTM [1202] [20].

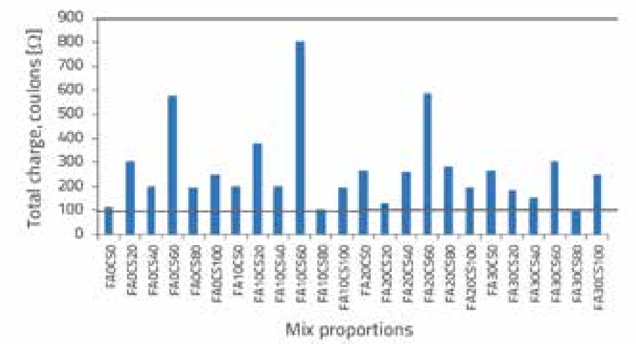


Figure 9. Chloride permeability values for concrete

As per the ASTM [1202-12], the chloride ion penetrability is based on the total charge passed on the concrete in "coulombs". If the charge passed is < 100 coulombs, the chloride ion penetrability is "negligible". The charge passed varying between 100 and 1000 coulombs is described as "very low", and the charge passed ranging from 1000 to 2000 coulombs is characterised as "low". The charge passed varying from 2000 to 4000 coulombs is considered as "moderate", and the charge passed of > 4000 coulombs is designated as "high". It could be inferred from the results that the chloride ion penetrations have less than 1000 coulombs for all concrete mixes. Total charges passed for 10 % and 30 % replacement of FA have very low values such as 102.6 coulombs and 101.7 coulombs, respectively, for 80 % fine aggregate replacement by CS. It can be concluded from these results that the combination of these two industrial waste materials performs well, and also that it reduces porosity in concrete. Thus the penetration of chloride ion is reduced and, hence, corrosion is prevented. FA is added as replacement for cement. It reacts with $Ca(OH)_2$ in the hydrated cement paste and forms complex compounds that reduce the permeability and improve the durability besides improving the economy of the mix.

Alkalinity

pH values of all mix proportions are shown in Figure 10. The pH values range from 10.2 to 12.5. It can be seen from the results that the pH value of all mix proportions decreases due to higher consumption of free lime ($Ca(OH)_2$) in concrete. The only advantage is that $Ca(OH)_2$, being alkaline in nature, maintains the pH value at around 13 in concrete, which prevents corrosion of reinforcement. However, the surplus calcium hydroxide reacts with sulphates present in the soil or water to form calcium sulphate, which further reacts with C_3A and causes deterioration of concrete. The use of blending materials such as fly ash, silica fume and other such pozzolanic materials is recommended so as to reduce the quantity of $Ca(OH)_2$ in concrete, and to overcome its bad effects by converting it into a cementitious product [4]. The pH value of pozzolanic concrete is much lower than that of ordinary concrete due to absence of free lime in concrete mix, which is not favourable for corrosion resistance of concrete reinforcement [21].

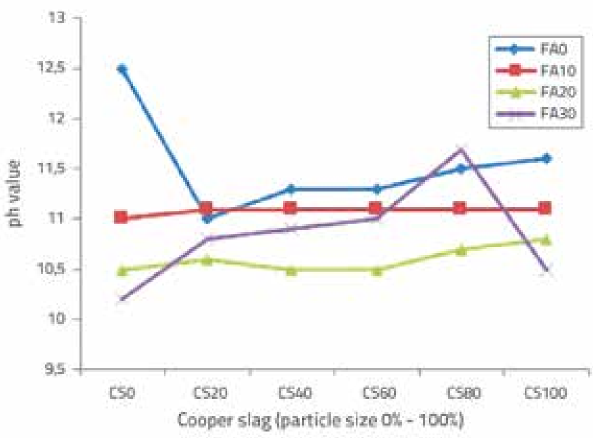


Figure10. pH values for concrete containing FA and CS

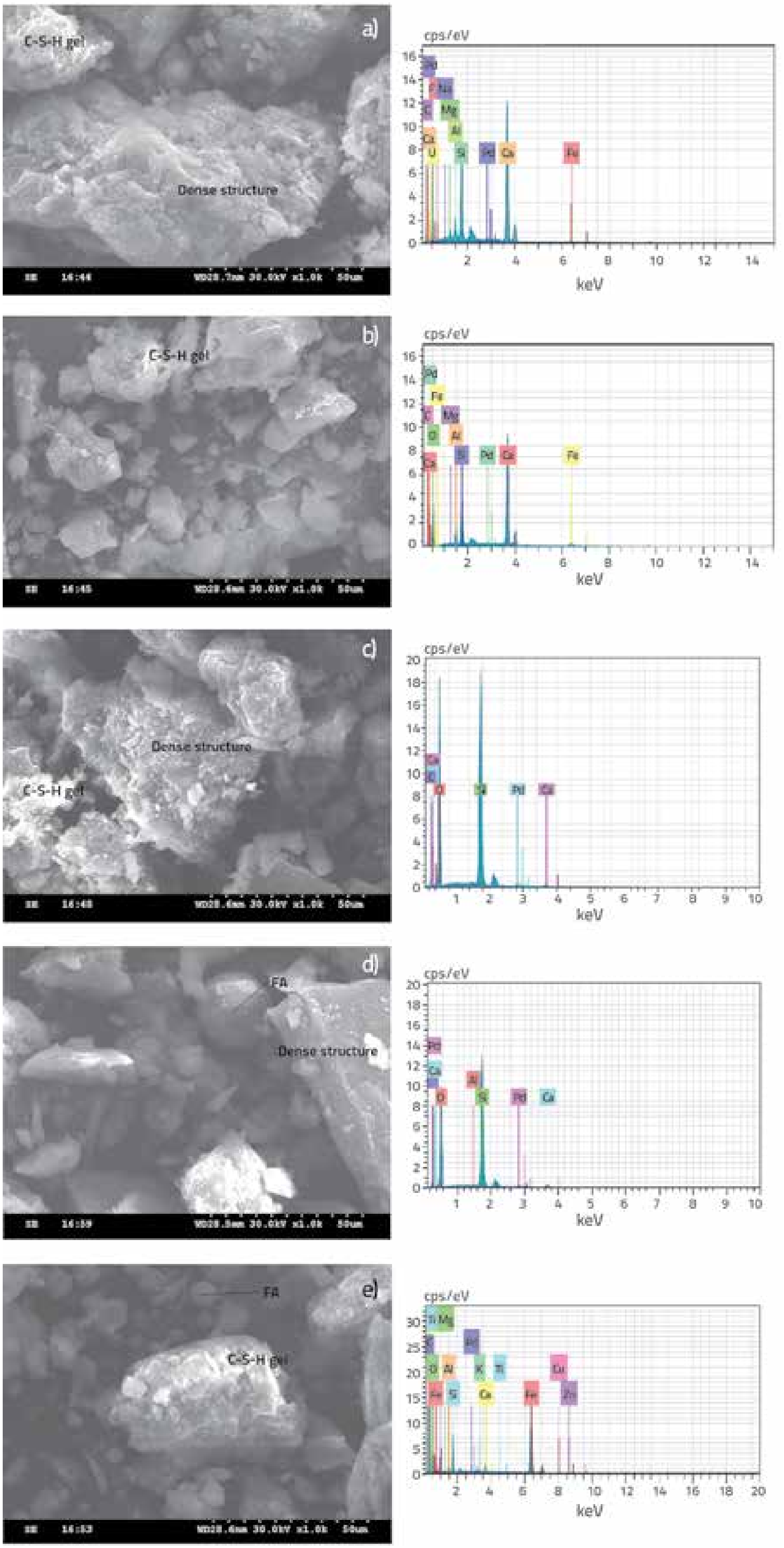


Figure 11. SEM and EDAX images for: a) FA0CS0; b) FA0CS80; c) FA10CS80; d) FA20CS80; e) FA30CS80

Microstructure of concrete

The microstructure study was conducted to observe the structure of concrete containing CS and FA. The Scanning Electron Microscopy (SEM) was used to record micrographs whereas the Energy dispersive X-ray spectroscopy (EDAX) was used for quantitative analysis. The results obtained by the EDAX analysis are presented as the atomic percentage of each element. Based on experimental results, concrete with 80 % and 100 % of CS substituted for fine aggregate behave better compared to other concretes. Thus the SEM and EDAX analyses were conducted for control concrete, minimum water absorption and porosity of samples at 90 days. The SEM image and typical EDAX spectra for elemental analysis of FA0CS0, FA0CS80, FA10CS80, FA20CS80 and FA30CS80 are given in Figure 11. It can be seen from these results that major components found in all specimens are Si, Ca, and Al. Other elements such as Na, Mg, Ti, Fe, and Pd are found in much smaller quantities. There were no great differences in the microstructure of all concrete mixes and, also, a major hydration product was found in all samples. In Figure 11.a for control concrete (FA0CS0), the hydrated cement paste is in the form of dense structure only. The EDAX analysis shows Si (36.02 %) as the only main element of this component.

In Figure 11.b and 11.c for FA0CS80 and FA10CS80, there are no unreacted fly ash particles, needle shaped ettringite and surplus $Ca(OH)_2$. It can be seen from these results that $Ca(OH)_2$ converts into secondary C-S-H gel by pozzolanic reaction and forms a continuous binding matrix. It is amorphous and fibrous and, hence, it has a large surface area resulting in generation of a discontinuous pore structure. Thus the microstructure changes greatly with incorporation of fly ash and CS. In Figure 11.d and 11.e for FA20CS80 and FA30CS80, there are a few un-hydrated FA and hydration products. It can be seen that most of the FA is consumed by the surplus lime and that the unreacted FA acts as micro-filler. Hence, concrete becomes denser and durability increases. Generally, there is no needle shaped ettringite and plate shaped $Ca(OH)_2$ in all images. It could be inferred from this that the permeability of concrete reduces with the use of pozzolanic materials in an optimum proportion. The pore refinement process occurs due to conversion of calcium hydroxide into secondary C-S-H gel by pozzolanic action.

5. Conclusion

The following conclusions can be drawn from this experimental investigation:

- Based on SWA and porosity tests, concrete with 100 % CS replacement for fine aggregate and 10 % and 20 % cement replacement by FA, is suitable for use in any severe environmental conditions. At the same time, concrete with 30 % FA and 40 % CS replacement for sand is considered as a poor concrete because of higher SWA (>5 %).
- Initially water absorption coefficient values are higher without FA and when fine aggregate is replaced by 80 % of CS. Finally, based on SWA, this mix proportion is considered good and the concrete structure is also capable of withstanding harmful effects in water prone areas.
- The unidirectional flow of water (sorptivity) of concrete with FA30 % and 100 % replacement for CS is similar to the control concrete. This mixture may be used as an economical mix.
- The RCPT test shows that, according to ASTM [C1202-12], the chloride ion penetration is very low and this mixture is suitable for seashore areas.
- pH values of all mix proportions vary from 10.5 to 11.7, except for the control concrete. This is not favourable for corrosion resistance of concrete because of higher consumption of surplus lime in concrete.
- The SEM and EDAX images show that durability properties of concrete improve when the combination of FA and CS is used. Only a few un-hydrated FA particles are present. This signifies that FA is consumed by the $Ca(OH)_2$ and gives additional C-S-H gel to the concrete. Hence, pore structure is reduced and dense structure is formed.
- Durability property tests carried out in this work prove the durability of the combination of CS and FA and that this concrete structure is cost effective.
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