Magazine of Civil Engineering. 2023. 118(2). Article No. 11801

Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

Research article

UDC 691.5

DOI: 10.34910/MCE.118.1

Performance of waste foundry sand concrete in sulfate environment

***J. Singh*[1]** ✉ **, *R. Siddique*[2]**

[1] *Chitkara University Institute of Engineering and Technology, Chitkara University, Punjab, India*

[2] *Thapar Institute of Engineering & Technology (Deemed to be University), Patiala, India*

✉ *jagdeep.singh71717@gmail.com*

Keywords: concrete, curing, compressive strength, durability, microstructure, scanning electron microscopy, x-ray diffraction

Abstract. Waste foundry sand is generated by the metal casting industry and has great potential to be used as a construction material. Nearly 70 % of the waste foundry generated is disposed of as a landfill which poses a threat to the surrounding environment. The negative impact of landfill disposal of waste foundry sand on the environment has invited the intentions of research faculty. In this research work, the impact of waste foundry sand as sand replacement on the properties of concrete cured in water as well as sulfate solution were explored. Test results indicate that the compressive strength of concrete cured in sulfate solution decreases with the use of waste foundry sand as partial substitution of natural sand. However, a chloride ion penetration resistance of concrete hikes on the accumulation of waste foundry sand. Up to 56 days, a concrete mixture made up of 15 % waste foundry sand showed optimum strength properties. Ultrasonic pulse velocities through concrete mixtures cured either in water or sulfate solution were almost identical. Energy dispersive spectroscopy analysis showed traces of sulfur in concrete mixtures cured in a sulfate solution.

Citation: Singh, J., Siddique, R. Performance of waste foundry sand concrete in sulfate environment. Magazine of Civil Engineering. 2023. 118(2). Article no. 11801. DOI: 10.34910/MCE.118.1

1. Introduction

Foundry sand (FS) is used to create molds for casting purposes in metal (ferrous and non-ferrous) casting industry. It is recycled and reused number of times till it loses its characteristics of consistency and cleanliness. When the foundry sand becomes unsuitable for reuse to create molds, it is discarded and disposed of as landfill. The non-usable foundry sand generated by foundries is called waste foundry sand. Worldwide, about 100 million tons of waste foundry sand [1] is engendered by the foundries by the year and India is the World's fourth-largest producer of waste foundry sand. Waste foundry is non-hazardous and is black in appearance. The physical properties of waste foundry sand are similar to river sand. The use of waste foundry sand in place of natural river sand will help in protecting the environment by reducing the mining of river sand.

Recently the researchers have made an attempt to utilize waste foundry sand as a substitute for natural sand in a concrete. Some published research studies by Khatib and Ellis [2], Aggarwal et al. [3], Guney et al. [4] and Naik et al. [5] show a decrease in concrete's strength characteristics made up of used foundry sand as a partial substitute of natural river sand. However, according to studies by Basar and Aksoy [6], Prabhu et al. [7], Prabhu et al. [8], and Torres et al. [9] without compromising mechanical properties of a concrete maximum 20 % waste foundry sand can be utilized as a substitute for natural sand. Another study by Mastella et al. [10] also reveals that the reduction in compressive strength of on concrete blocks containing up to 75 % waste foundry sand was not considerable. However, there are some studies by

Etxeberria et al. [11], Singh and Siddique [12], Kaur et al. [13], and Siddique et al. [14] show an increase in strength properties of concrete made with up to 20 % waste foundry sand. An investigation by Siddique et al. [15] exhibits a marginal increase in some strength properties of concrete incorporating waste foundry sand. According to the study by Siddique and Sandhu [16] higher compressive strength can be achieved with 10 % incorporation of used foundry sand in self-compacting concrete and concrete mixtures made with higher substitution levels i.e. 15 and 20 % exhibited lower compressive strength. Most of the studies on the use of waste foundry sand in concrete are focused on strength properties. Limited data is available related to the investigation on resistance of concrete made with waste foundry sand against chemical attacks such as acid, sulfate attack. However, these studies on resistance of concrete against sulfate attack show contradictory findings. According to the study by Prabhu et al. [8] reduction in compressive strength can be observed with the use of used foundry sand in the sulfate environment. Whereas, the study by Thaarini and Ramasamy [17] shows no negative effect on the resistance of geopolymer concrete made with waste foundry sand against sulfate attack. Another study by Smarzewski and Barnat-Hunek [18] indicates an improvement in the resistance of concrete against sulfate with use of waste foundry sand.

Intensive literature is available related to mechanical characteristics of concrete incorporating waste foundry sand. Limited data is available related to durability properties such as resistance of concrete incorporating waste foundry sand against acid and sulfate attack. The present investigation related to concrete has been carried out to assess the impact of waste foundry sand on sulfate resistance. The study evaluates the compressive strength, ultrasonic pulse velocity, chloride ion penetration, expansion, and microstructure of concrete incorporating waste foundry sand cured in water and 10 % sulfate solution.

2. Methods

2.1. Materials

In the study Ordinary Portland cement was used who's specifications are affirming to Indian code IS 8112: 2013. Cements characteristics were gauged as per Indian codes IS 4031(Part 1): 1996 and IS 4031 (Parts 3 to 6) and are presented in Table 1. Coarse aggregates with a maximum size of 20 mm confirming to IS 383:1970, was used. Physical characteristics of natural sand, coarse aggregate, as well as waste foundry sand were evaluated in line with Indian Standards IS 2386 (Part 3):1987 and are mentioned in Table 2. Waste foundry sand's chemical constitution is shown in Table 3. The grain size distribution curves of coarser aggregate, river sand as well as of waste foundry sand are presented in Fig. 1. Waste foundry sand's SEM morphology and EDS analysis is presented in Fig. 2 and 3, respectively. Properties of the sodium sulfate used in the investigation are mentioned in Table 4.

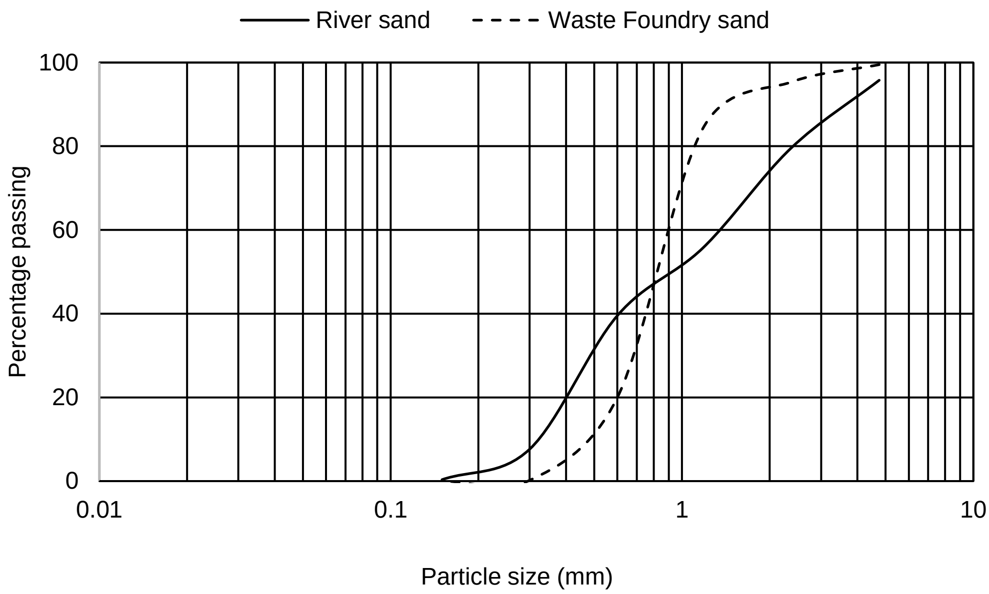

Figure 1. Particle size distribution curves of river sand and waste foundry sand.

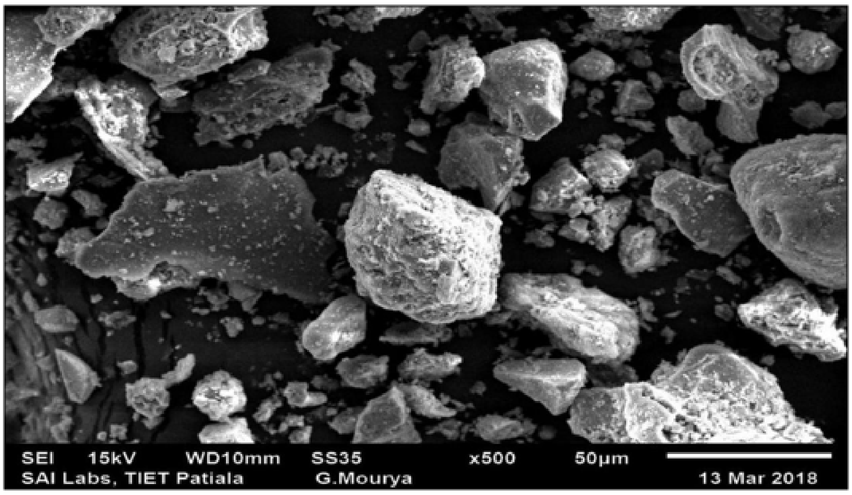

Figure 2. Scanning electron microscopy image of waste foundry sand.

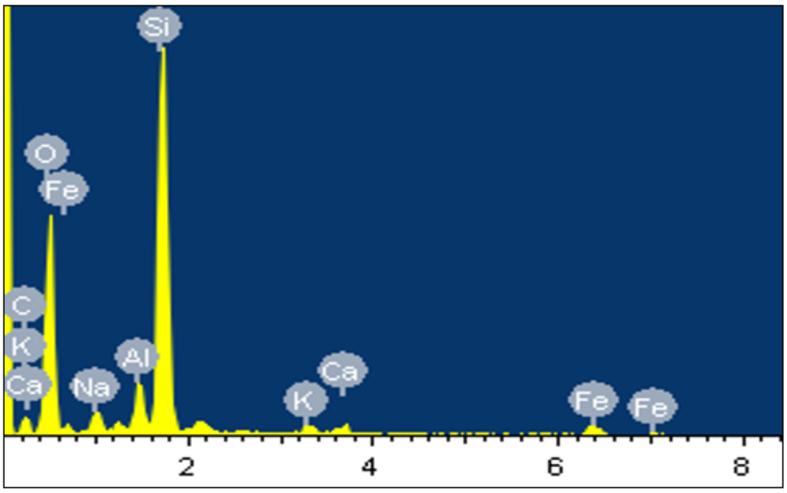

Figure 3. Energy dispersive X-ray spectroscopy chemical characterization spectrum of waste foundry sand.

Table 1. Properties of OPC.

Physical property	Result values	Standard values (BIS 8112: 2013)
Fineness (Retaining on 90 µ Sieve (%))	1.2	10 Max
Standard consistency (%)	29	–
Soundness (mm)	2.7	10 Max
Specific gravity	3.06	–
Initial setting time (min.)	75	30 Min
Final setting time (min.)	235	600 Max
Compressive strength 7-days (MPa)	32.6	33 Min
Compressive strength 28-days (MPa)	41.5	43 Min
Color	Gray	–

Table 2. Physical characteristics of coarse aggregate, river sand and waste foundry sand.

Property	Coarse aggregate		River sand	Waste Foundry sand
	10 mm	20 mm		
Specific gravity	2.68	2.59	2.54	2.8
Water absorption (%)	1.44	1.01	1.03	1.43
Fineness modulus	6.23	6.88	3.21	3.0
Bulk density (kg/m^3)	–	–	1784	1454

Table 3. Chemical properties of waste foundry sand.

Compound	Value (%)
SiO_2	77.22
Al_2O_3	1.84
FeO	8.10
CaO	6.4
TiO_2	0.23
MgO	0.25
Na_2O	2.59
K_2O	1.3
SrO	0.47
MnO	0.08

Table 4. Properties of sodium sulfate.

Property	Value
Chloride (%)	< 0.002
Heavy metals (%)	< 0.001
Arsenic (%)	< 0.0002
Calcium (%)	< 0.005
Iron (%)	< 0.001
Magnesium (%)	< 0.01
Loss on drying at 130ºC	< 1
PH (5% Water)	– 7.5

2.2. Mix proportioning, casting and curing

In the investigation concrete of strength 25 MPa after 28 days was considered as a control concrete and the concrete was designed as per IS 10262: 2009. 5, 10, 15, and 20 % quantity of waste foundry sand was used in the investigation as a substitute for natural river sand. In Table 5 the quantity of ingredients used in the concrete are mentioned. To evaluate the compression strength as well as the ultrasonic pulse velocity of concrete, cubes of size 150 mm were prepared. For determining the chloride-ion permeability cylindrical shaped samples of 200 mm length and 100 mm cross-section were used. Prism specimen of size 75×75×285 mm were cast to determine the expansion of concrete.

Table 5. Mix proportions of concrete.

Concrete mix	Cement (kg/m^3)	WFS (%)	Fine aggregate (kg/m^3)	WFS (kg/m^3)	Coarse aggregate (kg/m^3)		W/C ratio	Water (kg/m^3)
					10 mm	20 mm		
Control concrete (CC)	456.1	0	509.8	0	454.16	681.24	0.42	191.58
FS5	456.1	5	484.31	25.49	454.16	681.24	0.42	191.58
FS10	456.1	10	458.82	50.98	454.16	681.24	0.42	191.58
FS15	456.1	15	433.33	76.47	454.16	681.24	0.42	191.58
FS20	456.1	20	407.84	101.96	454.16	681.24	0.42	191.58

2.3. Testing procedure

Compressive strength was evaluated after proper curing as per Indian standard BIS 516: 1959. The procedure adopted to evaluate chloride-ion permeability was as per ASTM C 1202-12 [29] (Test standards are in Table 6) and the samples were tested after 7, 28, and 56 days. Expansion of concrete and ultrasonic pulse velocity were determined as per ASTM C 1012-10 [30] and ASTM C 597-02 [31], respectively. X-ray diffraction pattern of powdered concrete passing through 60 µm sieve was recorded with X-ray diffractometer with CuKα radiation (λ = 1.54 Å) at diffraction angle 2θ varies from 10° to 70° in steps of 2θ = 0.013°. X'PertHighScore Plus software tool was used to analyze the phases present in concrete. Scanning electron microscope instrument was used to examine the framework of different phases that exists inside the hard concrete.

Table 6. Chloride permeability classification (ASTM C 1202-12) [29].

Charge passed (coulomb)	Chloride permeability
< 100	Negligible
100-1000	Very low
1000-2000	Low
2000-4000	Moderate
> 4000	High

3. Results and Discussion

3.1. Characterization of material

Waste foundry sand is mainly composed of silica (77.22 %), iron oxide (8.14 %), calcium oxide (6.4 %), and aluminum oxide (1.84 %) and small traces of magnesium oxide, manganese oxide, potassium oxide. The fineness modulus and specific gravity of waste foundry sand were 3.0 and 2.8, compared to 3.21 and 2.54 of river sand, respectively. Water absorption of river sand is less comparative to waste foundry sand. The particles of waste foundry sand are sub-angular to angular in shape. Some platy particles of waste foundry sand were observed in the SEM image. The rough-surfaced particles of waste foundry sand improve the bond with the paste. All the above stated information is mentioned in the section 2.1. in detail.

3.2. Compressive strength

3.2.1. Concrete cured in water

Fig. 4 shows the compressive strength of concrete incorporating was as fine aggregates at 7, 28, and 56 days of normal water curing. It is evident from Fig. 4, that the compressive strength of concrete increases with an increase in up to 20 % waste foundry sand content. Concrete mixture FS15 displayed optimum compressive strength at the all curing periods. As compared to control mix (CC), different mixes named as FS5, FS10, FS15, and FS20 shows 1.14 %, 3.42 %, 7.6 %, and 0.8 % more compressive strength at a curing period of only 7-days, respectively. At 28-days, these concrete mixes exhibited compressive strength of 33.8, 34.7, 36.5, and 34.8 MPa, respectively, and the control mix (CC) shows 33.65 MPa strength. At 56-days, concrete mixtures FS5, FS10, FS15, and FS20 showed 3.8 %, 6.2 %, 10 %, and 2.1 %, respectively, higher compressive strength comparative to control mix (CC). The improvement in compressive strength of concrete having waste foundry sand can be attributed to the packing effect of particles of waste foundry sand. At 28-days, hike in the value of compression strength of different concrete mixes FS5, FS10, FS15, and FS20 with respect to that at 7 days was 27.06 %, 27.57 %, 28.97 %, and 31.3 %, respectively, compared to 27.94 % of control mix (CC). Similarly, at an age of 56-days, positive impact on compressive strength was observed as 51.12 %, 29.04 %, 50.05 %, and 43.01 %, respectively, 47.1 % of control concrete as compare to compressive strength at 7-days.

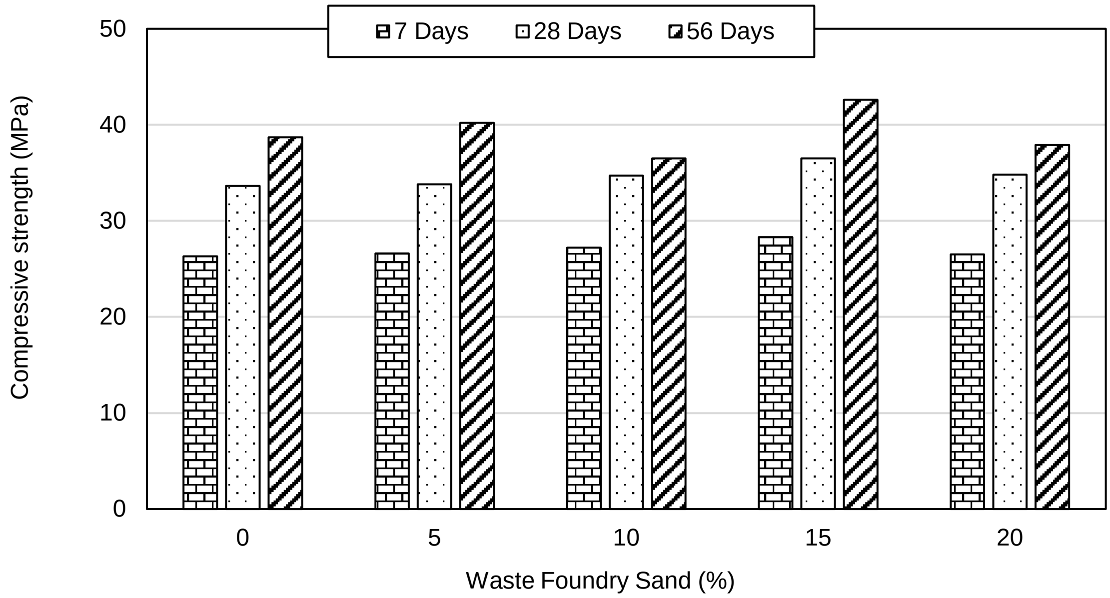

Figure 4. Compressive strength of water cured concrete mixtures.

3.2.2. Concrete immersed in 10 % sodium sulfate solution after initial 28 days of water curing

Concrete's compressive strength comprises of different waste foundry sand content cured in sulfate solution up to 7, 28, and 56 days is presented in Fig. 5. No negative impact of waste foundry sand on concrete's compression strength can be seen in Fig. 5 till 28-days of curing in 10 % sodium sulfate solution. A same increasing trend can be observed in all mixes till 56-days of curing in a sulfate solution. It can be noticed that till the replacement level of 15 %, compressive strength of waste foundry sand concrete improved even after immersion in 10 % sulfate solution up to 56 days. After 7 days of immersion, concrete mixtures FS5, FS10, FS15, and FS20 displayed compressive strength of 30.2, 33.6, 36.7, and 34.6 MPa, respectively and the control mix shows 27.4 MPa strength. Alike fashion was seen even after 28-days of sulfate curing. Hike in compression strength after 28-days sulfate curing of different mixes FS5, FS10, FS15 and FS20 with respect to control concrete was 6.60 %, 8.70 %, 16.81 % and 15.31 %, respectively. Strength of concrete mixes CC, FS5, FS10, FS15, and FS20 were 44.5, 41.1, 42.8, 44.6, and 39.2 MPa after 56-days of sulfate curing. From the results, it can be contemplated that concrete containing waste foundry sand shows more compressive strength even beyond 28-days of curing in sulfate medium. The concrete mixture FS15 exhibited optimum compressive strength at all the periods of curing in 10 % sulfate solution. This trend of compressive strength in all concrete mixtures indicates that the hydration process continued even during immersion in 10 % sodium sulfate solution.

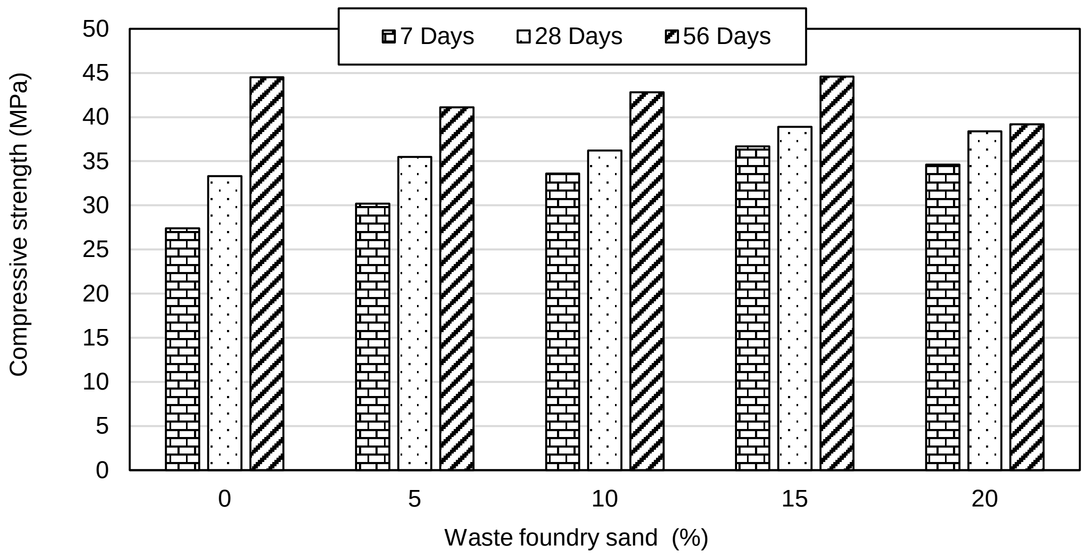

Figure 5. Compressive strength of concrete mixture after immersion in 10% sulfate solution.

3.2.3. Comparison of compressive strength of concrete cured in 10% sodium sulfate and normal water after initial water curing of 28 days

Before determining the compressive strength, all the concrete samples were firstly cured in normal water for 28-days and then some of the samples were water cured and some of they were cured in 10 % sodium sulfate solution, results are shown in Fig. 6 to 7. At 35 days of the total age of curing i.e. water curing for 28-days and sulfate curing for 7-days, concrete mixtures control concrete, FS5, FS10, FS15 and FS20 showed a decrease of 24.31, 19.25, 10.16, 3.4, and 5.72 % in compressive strength comparative to corresponding concrete mixtures cured in normal water. Similarly, at 56 days of age i.e. 28-days of water curing and 28-days of 10 % sulfate curing, a decrease in compression strength of these concrete mixes were 13.95, 11.69, 11.92, 8.69 and 1.28 % relative to those concrete samples which were normal water cured. At 84 days of age, the margins in concrete's compressive strength after water and 10 % sulfate solution curing reduced to 2.84, 3.29, 1.38, 4.29, and 2.73 %, respectively. In both types of curing conditions results reveal a similar trend of increase in compressive strength. But a rise in compressive strength of 10 % sulfate solution cured concrete was comparatively less than that of normal water cured concrete. It could be due to higher concentration of sulfate solution which may lead to more absorption of sulfate ions by C-S-H gel and thus make C-S-H gel of lower quality i.e. binding ability of the gel reduces [32]. High sulfate content also hinders in early hydration of binder or C_3A and thus results in lesser compressive strength [33, 34].

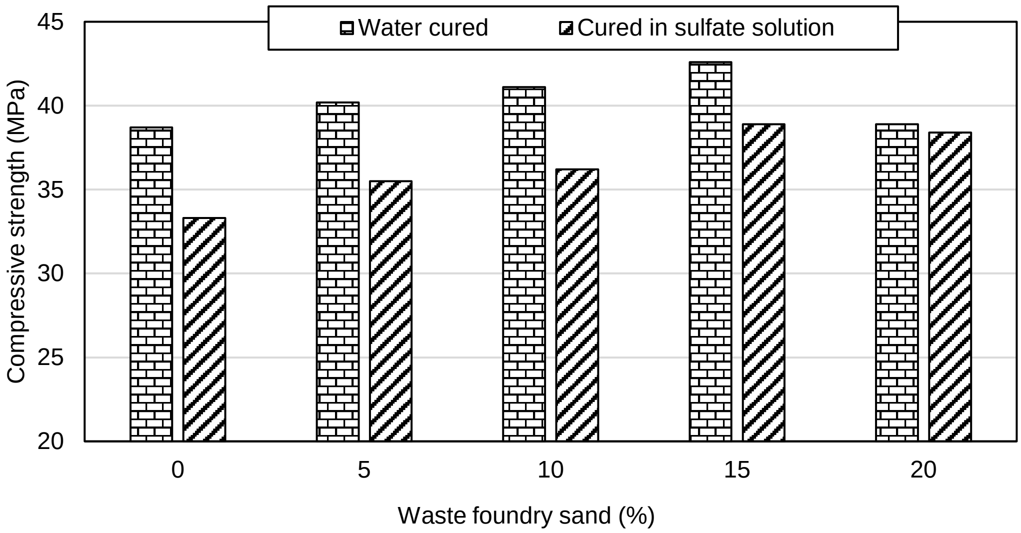

Figure 6. Compressive strength of concrete mixture after immersion in 10% sulfate solution and water at total age of 56 days.

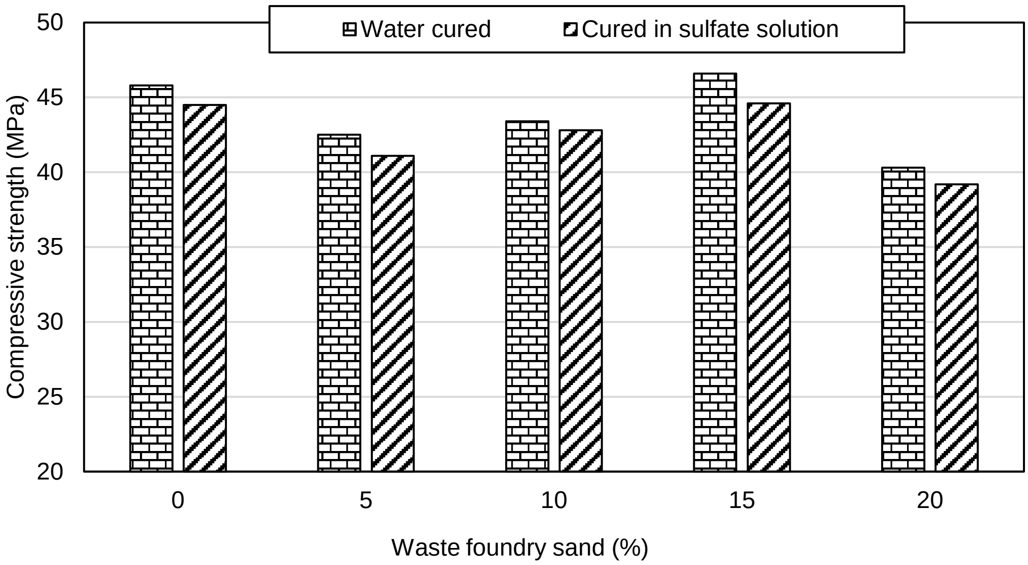

Figure 7. Compressive strength of concrete mixture after immersion in 10% sulfate solution and water at total age of 56 days 84 days.

3.3. Expansion of concrete specimens

3.2.4. Concrete cured in sulfate solution

Change in dimensions of a concrete specimen is a key factor to assess the impact of sulfate attack. The change in length of prism specimens of various concrete mixtures cured in 10 % sulfate solution after initially curing in water for 28 days is presented in Fig. 8. After curing for 28-days in 10 % sulfate solution, control concrete FS5, FS10, FS15 and FS20 exhibited expansion strain of 87.72×10^{-6}, 70.175×10^{-6}, 70.175×10^{-6}, 52.631×10^{-6} and 94.736×10^{-6}, respectively. After 56 days of immersion these figures increased to 105.263×10^{-6}, 87.72×10^{-6}, 98.245×10^{-6}, 70.175×10^{-6} and 105.263×10^{-6}, respectively.

As per the test results mixture FS15 exhibited minimum expansion whereas control concrete and FS20 mixtures showed maximum expansion after 56 days of immersion. The expansion of concrete cured in sulfate solution occurs due to formation of ettringites inside concrete on reaction with sulfate ions, these by-products formed so are expansive or swallowing in nature, so it may cause an expansion in concrete.

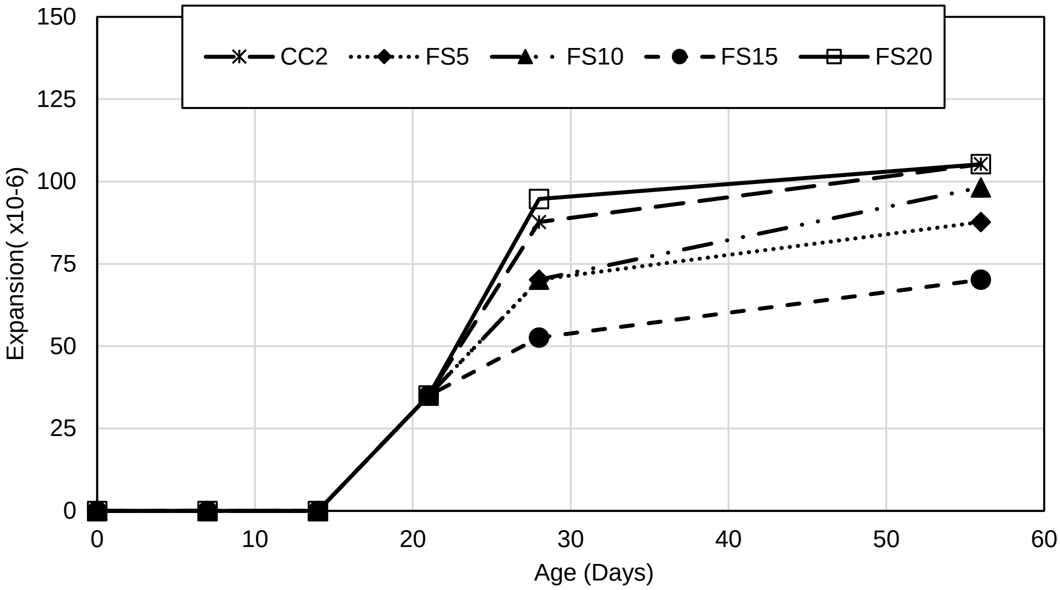

Figure 8. Concrete's expansion after cured in 10% sulfate solution.

3.2.5. Comparison of expansion of concrete cured in 10 % Sodium Sulfate and Water

Expansion of concrete prisms was also examined under water curing in a similar way as was done for concrete mixtures cured in 10 % sodium sulfate. After 84 (28+56) days of total age, control concrete, FS5, FS10, FS15 and FS20 cured in water exhibited expansion strain of 45.614×10^{-6}, 35.087×10^{-6}, 45.614×10^{-6}, 45.614×10^{-6} and 70.175×10^{-6}, compared to 105.263×10^{-6}, 87.72×10^{-6}, 98.245×10^{-6}, 70.175×10^{-6} and 105.263×10^{-6} expansion strain shown by these concrete mixes after curing in 10 % sulfate medium for a period of 56-days prior to this, 28-days normal water curing was done. The difference in expansion of concrete mixtures cured in sulfate solution and water can be considered as the expansion due to the action of sulfate. Afterward 56-days of 10 % sulfate solution curing, the net expansion of concrete mixes FS5, FS10, FS15, and FS20 due to sulfate attack was 52.633, 52.631, 24.561 and 35.088, respectively, compared to 59.649 of control concrete.

3.4. Chloride ion permeability

3.2.6. Concrete cured in water

The test results of Waste foundry sand concrete are presented in Fig. 9. It can be observed in Fig. 9 that with an increase in age and with the inclusion of waste foundry sand, chloride ion permeability reduces. Concrete mixture FS15 displayed the lowest chloride ion permeability at all the curing ages. Concrete mixes FS5, FS10, FS15, and FS20 showed 4.65, 14.95, 23.27, and 25 % reduction in total charge passed compared to that of control concrete after 7-days of curing. At 28-days of curing, charge flows across concrete mixes were 2196, 2078, 2042, and 2140 Coulomb, respectively, compared to 2205 Coulomb for control concrete (CC). At 56-days there was 9.57 %, 15.65 %, 20.37 %, and 12.4 %, reduction in charge flow in concrete mixes, compared to control concrete. With an increase in age from 7 days to 28 days of different concrete mixes, the reduction in charge flow was 37.7 %, 35 %, 31.05 %, 24.9 % and 19.45 % respectively. Similarly, at 56 days, chloride ion passing ability through these concrete mixtures reduced by 41.95 %, 44.95 %, 42.43 %, 39.75 % and 32.18 % compared to that at 7 days.

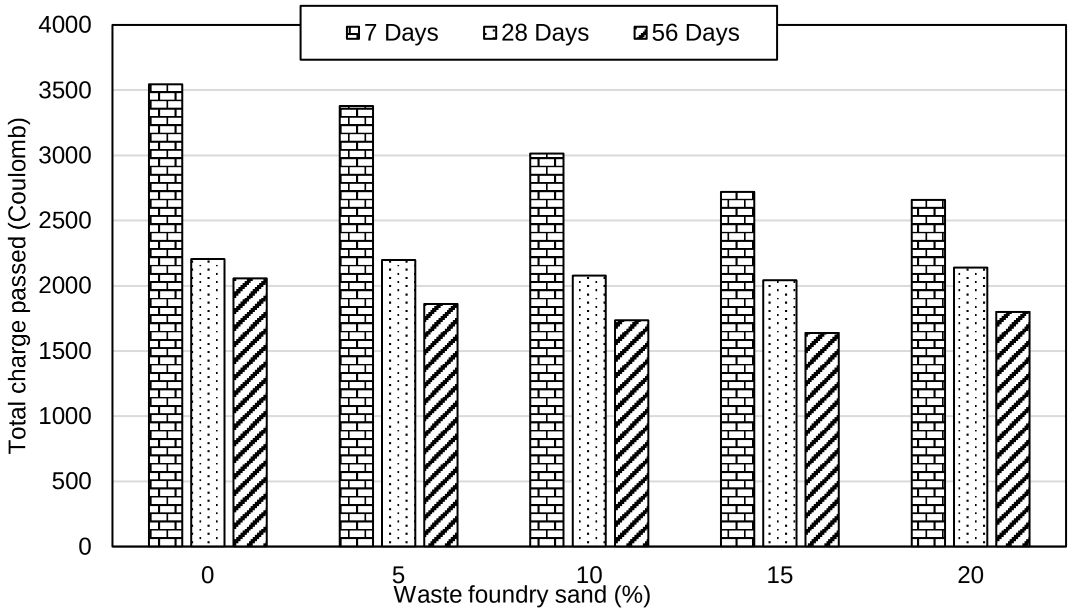

Figure 9. Total charge passed through concrete mixtures cured in water.

3.2.7. Concrete immersed in 10 % sodium sulfate solution after initial 28 days of water curing

In Fig. 10 results of chloride ion permeability are shown, in which concrete mixes were firstly water cured for 28-days and then cured in 10 % sodium sulfate solution. Total charge passed through control concrete, FS5, FS10, FS15 and FS20 was 2125, 1998, 1822, 1668, and 1688 Coulomb, respectively, after 7-days of sulfate curing. Charge flows through concrete mixes was 1822, 1725, 1728, 1503 and 1561 Coulomb, respectively after 28-days of sulfate curing. Similarly, after 56-days of immersion, charge flow were 1522, 1199, 829, 811, and 964 Coulomb, respectively. According to ASTM C 1202-12 [29], after 7 and 28 days of immersion, concrete mixtures showed moderate chloride ion permeability. After 56 days of immersion, control concrete and concrete mixture FS5 showed low chloride ion permeability whereas concrete mixtures FS10, FS15, and FS20 exhibit very low chloride ion penetration in line with ASTM C 1202-12 [29]. The reduction in charge passing ability may be as sulfate solution penetrate inside microstructure of concrete and then sulfate particles may crystallize inside concretes voids or fissure and make concrete more impermeable.

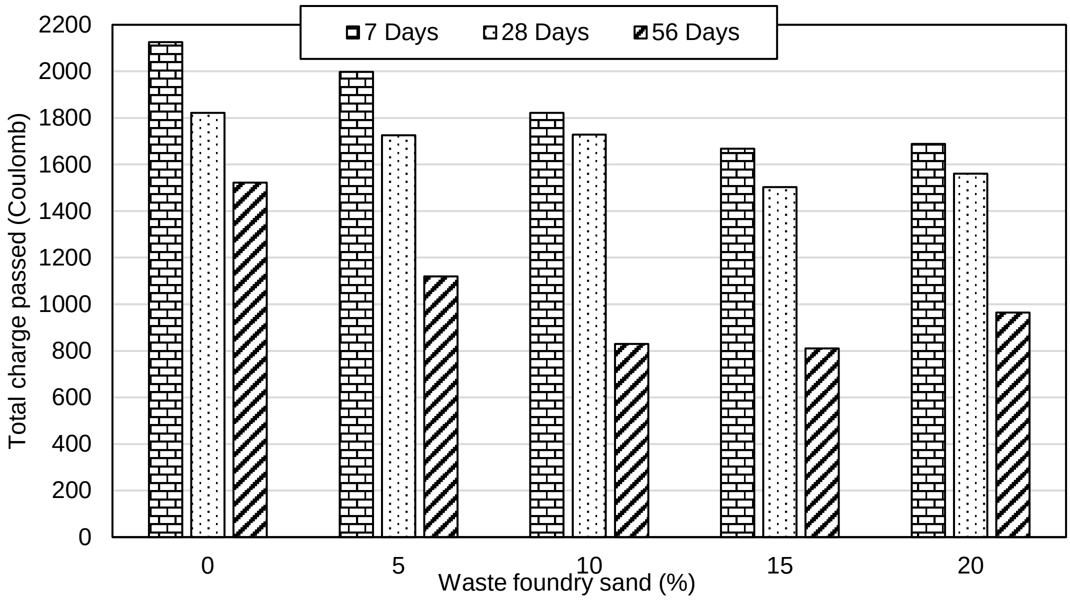

Figure 10. Total charge passed through concrete mixtures cured in 10% sulfate solution after initial water curing of 28 days.

3.2.8. Comparison of chloride ion permeability of concrete cured in 10 % sulfate solution and water

To compare the chloride ion permeability of concrete mixtures cured in water and in 10 % sulfate solution, rapid chloride penetration tests were performed on different concrete mixes at an equivalent age. Total charge passed through concrete mixtures immersed in sulfate solution and cured in water are presented in Fig. 11 and 12. At 35 days of total curing age i.e. 28-days of initial water curing after that 7 days of sulfate curing, charge flow though control concrete, FS5, FS10, FS15, and FS20 was 2125, 1998, 1822, 1668, and 1688 Coulomb, respectively. When these concrete mixture was cured in water up to 35 days, the values of charge passed were 2168, 1908, 1889, 1702 and 1722 Coulombs, respectively. Similarly, at 84 days of total curing age, total charge passed through control concrete, FS5, FS10, FS15, and FS20 immersed in sulfate solution was 1522, 1119, 829, 811, and 964 Coulombs compared to 1481, 1407, 1238, 1189, and 1473 coulomb of charge passed through concrete mixtures cured in water. In both types of curing, a concrete mixture containing 15 % waste foundry sand displayed the lowest total charge passed.

After total curing of 56-days, mixes FS5, FS10, FS15, and FS20 cured in 10 % sulfate solution showed a decrease of 7.25, 6.5, 11.74, and 8.66 % in total charge passed comparative to corresponding concrete mixtures cured in normal water, respectively. The control concrete mixture displayed 8.8 % decrease in total charge passed when immersed in 10 % sulfate solution compared to charge flows through a water cured sample of concrete. Similar trend of decrease in chloride permeability was noticed after 84-days of curing. Less charge penetration through different concrete mixes cured in sulfate solution may be due to the formation of ettringite along with hydrates of calcium silicate in empty spaces in concrete microstructure and thus making the concrete more non-porous. Sulfate particles may also crystallize in voids in concrete and make the concrete more impermeable.

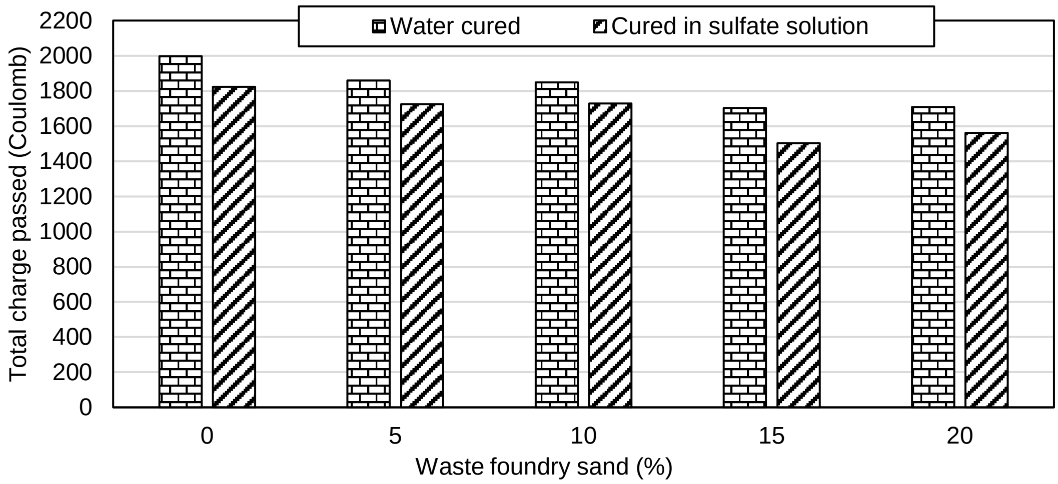

Figure 11. Total charge passed through concrete mixtures cured in water and 10% sulfate solution at total age of 56 (28+28) days.

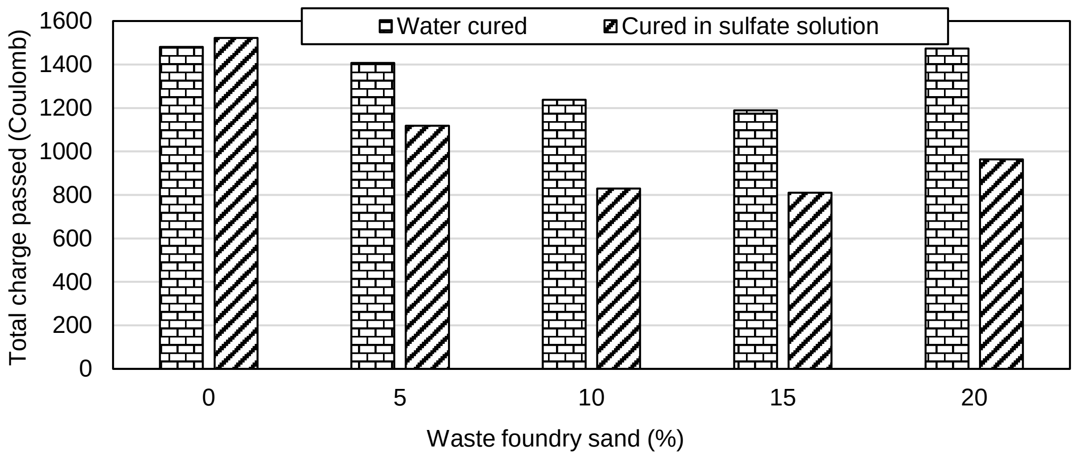

Figure 12. Charge flow through concrete mixes cured in water as well as in 10% sulfate solution at total age of 84 (28+56) days.

3.5. Ultrasonic Pulse Velocity

3.2.9. Concrete cured in water

Pulse velocity values of concrete incorporating waste foundry sand as a substitute of river sand are presented in Table 7. Concrete mixtures FS15 displayed optimum value of ultra-sonic pulse velocity at all curing ages. However, there were no major changes observed in pulse velocity values with the use of waste foundry sand in concrete. After 7-days of curing increase in the value of pulse velocity of different concrete mixes FS5, FS10, FS15, and FS20 were 0.32, 0.40, 0.73, and 0.32 % compared to that of control concrete. At 28 days of curing age, pulse velocity of waste foundry sand concrete mixtures was 6220, 6260, 6280, and 6255 m/s, compared to 6200 m/s of control concrete, respectively. At 56 days of curing age, pulse velocity of waste foundry sand concrete mixtures was higher by 0.47 %, 0.79 %, 1.26 %, and 0.79 % than that of control concrete. With the rise in curing duration from 7 days to 56 days, waste foundry sand concrete mixtures displayed 2.66 %, 2.9 %, 3.0 %, and 2.98 % increase in pulse velocity compared to control concrete whose rise is 2.5 %. Higher values of pulse velocity indicate that denser the microstructure of concrete mixtures.

Table 7. Comparison of pulse velocity of concrete mixtures immersed in 10% sodium sulfate solution after initial 28 days water curing and cured in water.

Age (days)	Sodium sulfate curing					Water curing				
	Pulse velocity (m/s)									
	CC	FS5	FS10	FS15	FS20	CC	FS5	FS10	FS15	FS20
28+7	6325	6333	6330	6360	6320	6300	6330	6360	6360	6272
28+28	6380	6380	6369	6440	6360	6335	6360	6380	6410	6360
28+56	6580	6580	6580	6610	6490	6520	6580	6520	6640	6520

3.2.10. Concrete immersed in 10 % sodium sulfate solution after initial 28 days of water curing

Pulse velocity values of concrete mixtures cured in 10 % sodium sulfate after the initial 28 days of water curing are mentioned in Table 7. Experimental results show that ultrasonic pulse velocity value increases with the rise in curing duration. However, it was observed that the pulse velocity of waste foundry sand concrete and control concrete as well, was almost the same at every age of immersion in a sulfate solution. This may be due to the reason that the sulfate particles may crystallize inside concretes voids and make concrete more impermeable and denser.

3.2.11. Comparison of pulse velocity of concrete cured in 10 % sulfate solution and water

To compare the pulse velocity of concrete mixtures cured in water and in 10 % sulfate solution, ultrasonic pulse velocity tests were performed on concrete specimens cured in water at an equivalent age. The pulse velocity of concrete mixtures immersed in sulfate and cured in water are presented in Table 7. It is evident from the Table 7 that no major change in the pulse velocities of different concrete mixes cured either in normal water or in 10 % sulfate solution at every equivalent age. After 7-days of 10 % sulfate curing, concrete mixes FS5, FS10, FS15, and FS20 displayed pulse velocity of 6333, 6330, 6360, and 6320 m/s, respectively, compared to 6325 m/s for control concrete. These concrete mixtures, when cured in normal water for total duration of 35 days, displayed pulse velocity of 6330, 6360, 6360 and 6272 m/s, respectively, compared to 6300 m/s for control concrete. According to IS 13311 (part-1): 1992 [(Standards are mentioned in Table 8), the quality of concrete mixtures either immersed in sulfate solution or cured in water can be termed as excellent at all the ages.

Table 8. Pulse velocity as concrete's quality grading (BIS 13311 (part-1)).

Pulse velocity (km/sec)	Concrete quality grade
> 4.5	Excellent
3.5-4.5	Good
3.0-3.5	Medium
< 3.0	Doubtful

3.6. Microstructure Analysis

Scanning electron microscopy, as well as Energy Dispersive Spectroscopy analysis, were performed on a small fractured sample of control concrete and concrete specimens FS5, FS10, FS15, and FS20 after 28 days of sodium sulfate curing and normal water curing. The specimens were placed on the SEM stubs and the gold layer was applied over it. To determine chemical compositions of different phases of concrete microstructure EDS was performed which approximately tells about the oxide composition of different compounds. Fig. 13 and 14 show SEM micrographs and EDS spectrum of control concrete mixture cured in 10 % sulfate solution. Fig. 15 and 16 show SEM micrographs and EDS spectrum of concrete mixture FS15 cured in 10 % sulfate solution. Fig. 17 and 18 show SEM micrographs and EDS spectrum of concrete mixture FS15 cured in water. The major phases present in concrete were Calcium silicate hydrate (CSH), Portlandite ($Ca(OH)_2$) and ettringnites etc. CSH looks like fibrous flakes, blocky mass, granular etc., calcium hydroxide appears like platy crystals and ettringnite were like a needle in shape. The morphologies of different phases have been identified and marked on SEM images. SEM images of concrete mixtures show CSH gel is uniformly scattered throughout the images. According to the study by Gurumoorthy and Arunachalam (2016) [36] CSH gel formation in concrete improves on the inclusion of waste foundry sand.

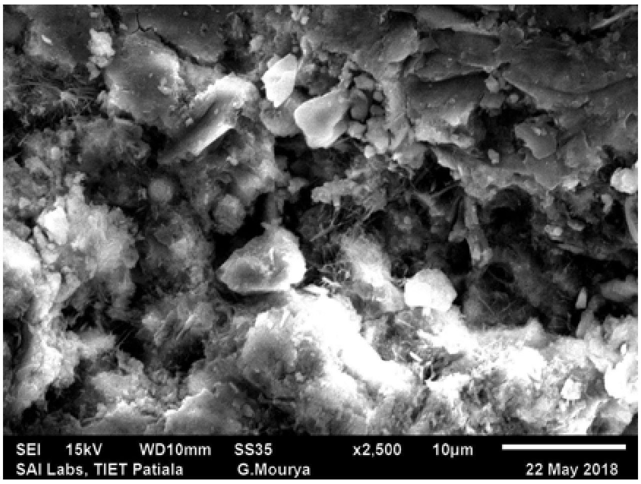

Figure 13. Scanning electron microscopy image of control concrete (CC) after 28 days of curing in sulfate solution after initial curing in water.

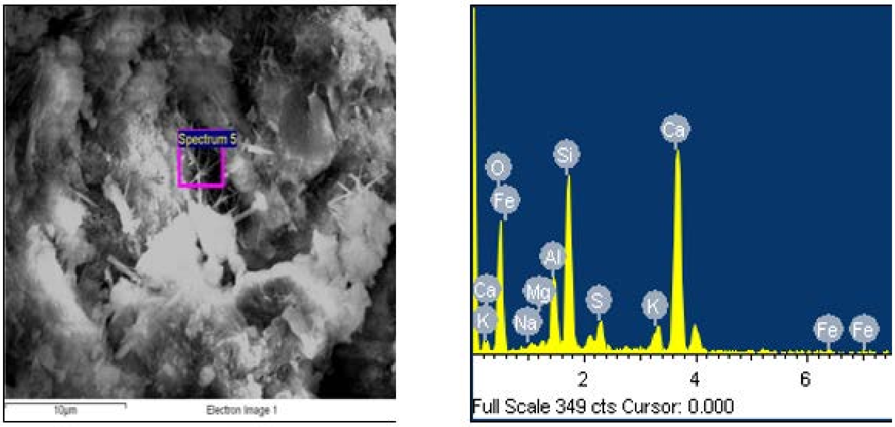

Figure 14. Energy dispersive X-ray spectroscopy spectrum of control concrete (CC) after 28 days of curing in sulfate solution after initial curing in water.

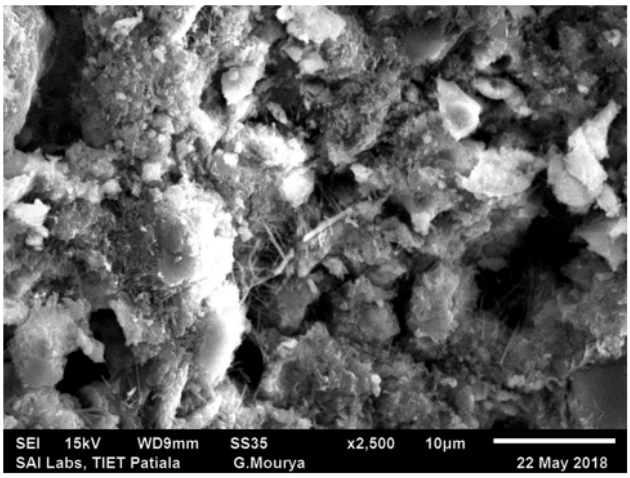

Figure 15. Scanning electron microscopy image of FS15 after 28 days of curing in sulfate solution after 28 days of initial water curing.

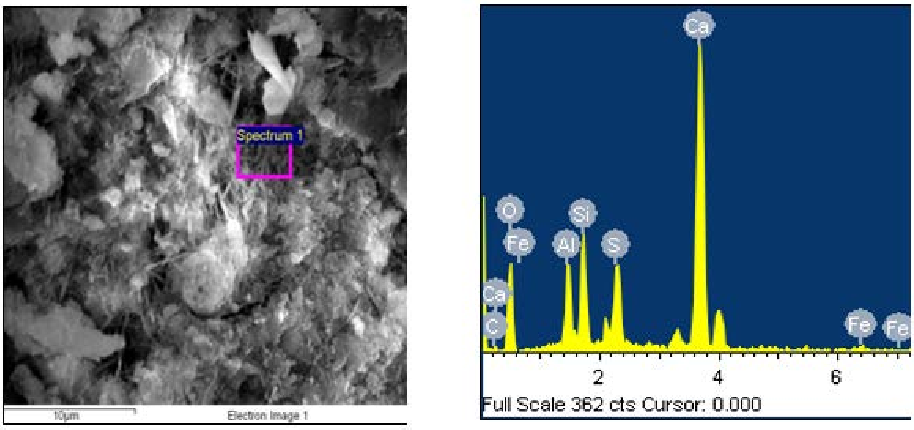

Figure 16. Energy dispersive X-ray spectroscopy spectrum of SF15 after 28 days of curing in sulfate solution after initial water curing.

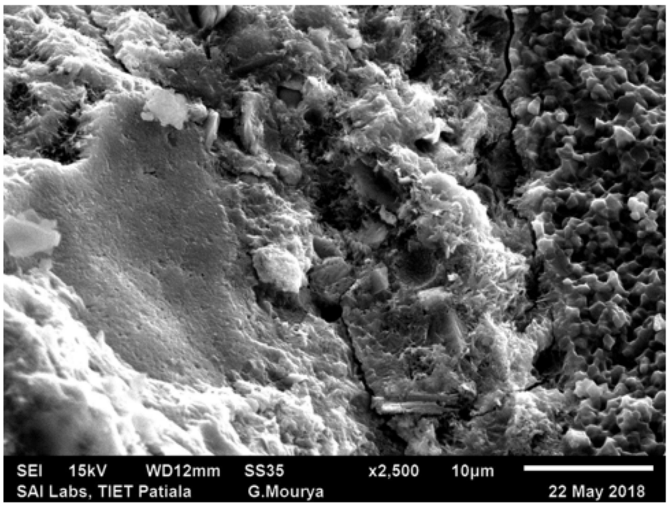

Figure 17. Scanning electron microscopy image of SF15 after 56 (28+28) days of water curing.

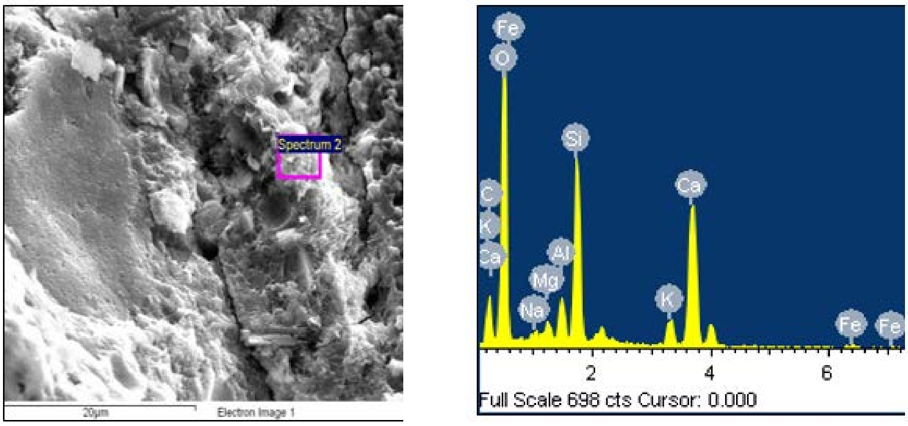

Figure 18. Energy dispersive X-ray spectroscopy spectrum of SF15 concrete after 56 (28+28) days of water curing.

Chemical characterization of concrete mixtures was determined at four/five locations on each sample by energy dispersive X-ray spectroscopy (EDS). The results of the elemental analysis carried out using EDS are presented in Table 9. The results show that no sulfur traces were detected in concrete mixtures except control concrete cured in water. Whereas, elemental analysis of concrete mixtures immersed in 10 % sulfate solution shows the presence of sulfur traces in all the concrete mixtures. Sulfur traces were detected at all the locations on control concrete, FS15, and FS20 concrete mixtures after sulfate curing. In the case of a concrete mixture FS10, sulfur traces were detected at three out of four locations. However, sulfur traces were detected at only one location on concrete mixture FS5 after immersion in a sulfate solution. Traces of sulfur detected by EDS analysis in concrete mixtures immersed in sodium sulfate solution shows that sulfate ion (SO_4^{2-}) entered inside a concrete microstructure.

Table 9. Chemical configuration of concrete after sulfate solution and water curing.

Element	Cured in 10 % sodium sulfate solution					Cured in water				
	Maximum / minimum composition by weight (%)									
	CC	FS5	FS10	FS15	FS20	CC	FS5	FS10	FS15	FS20
Ca	30.63/ 16.96	27.38/ 17.31	53.40/ 2.58	41.28/ 25.34	32.27/ 19.97	43.45/ 20.15	23.19/ 5.57	48.77/ 16.72	17.26/ 17.11	31.98/ 18.97
Si	14.72/ 9.53	12.88/ 8.77	22.50/ 7.26	11.86/ 6.92	19.89/ 0.82	8.73/ 1.68	14.74/ 4.68	19.80/ 4.62	11.01/ 9.67	12.48/ 8.78
Al	6.33/ 2.66	5.38/ 1.70	16.98/ 2.66	4.67/ 2.60	13.10/ 2.71	2.51/ 0.42	11.21/ 2.12	7.7/ 0.88	5.26/ 2.21	4.17/ 2.32
K	2.73/ 1.17	2.01/ 1.09	2.66/ 2.33	1.59/ 1.46	2.32/ 1.82	3.62/ 0.07	1.35/ 0.74	–	2.62/ 1.69	2.24/ 1.48
O	59.85/ 45.49	60.31/ 51.63	49.97/ 23.94	52.28/ 36.56	57.47/ 41.44	55.86/ 51.34	60.23/ 53.47	52.17/ 34.42	61.92/ 59.02	56.92/ 49.22
C	8.29/ 0.88	10.13/ 0.79	6.66/ 1.68	3.10/ 1.34	4.71/ 2.93	8.25/ 1.59	5.71/ 0.58	7.99/ 3.35	6.13/ 0.25	0.46/ 0.13
S	2.47/ 0.56	1.46/ 0.0	7.0/ 1.65	6.37/ 0.81	2.37/ 0.42	0.31/ 0.10	–	–	–	0.57/ 0.0
Mg	0.78/ 0.26	0.67/ 0.19	1.13/ 0.46	0.76/ 0.18	1.59/ 0.10	0.89/ 0.11	1.49/ 0.14	0.30/ 0.08	0.76/ 0.63	2.77/ 0.27
Fe	3.14/ 0.72	3.38/ 0.96	3.04/ 0.62	1.91/ 1.20	2.56/ 1.43	0.91/ 0.0	25.99/ 1.17	4.01/ 0.41	1.68/ 1.07	4.29/ 2.67
Na	0.43/ 0.14	0.15/ 0.05	0.45/ 0.19	0.41/ 0.15	0.71/ 0.05	0.47/ 0.35	0.15/ 0.09	0.23/ 0.0	0.33/ 0.22	0.53/ 0.16

Fig. 19 to 22 present the XRD spectrum of concrete mixtures. The XRD spectrum of concrete mixtures shows weak peaks of ettringite and no peak of gypsum and thaumasite which indicates that no major damage was caused by sulfate attack till 28-days. Most commonly compounds seen in the analysis are quartz (Q), portlandite (P), CSH gel (CSH), calcite (C), and ettringnite (E). The presence of CH indicates the hydration process of cement and the absence of gypsum indicates that no reaction taken place between sulfate ions and portlandite in all sulfate cured samples. It can also be predicted that CSH gel absorbs sulfate ions and thus degrades its quality and binding ability, due to this content of sulfate ions reduced in the solution and thus gypsum will not form and $Ca(OH)_2$ remain unreacted [34].

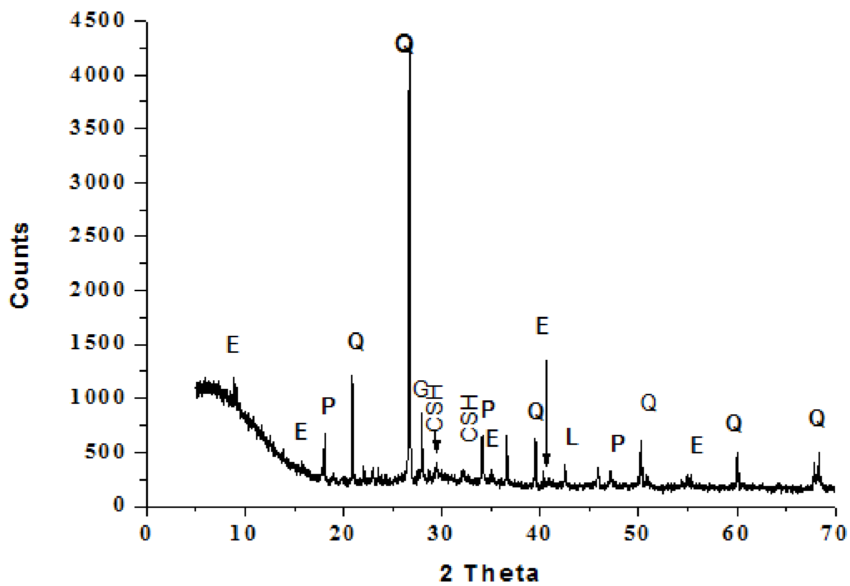

Figure 19. XRD spectrum of control concrete cured in sulfate solution for 28 days after curing in water for 28 days (E is Ettringite, Q is Quartz, P is Porlandite, C is Calcite, CSH is Calcium silicate hydrate, G is Gismondine).

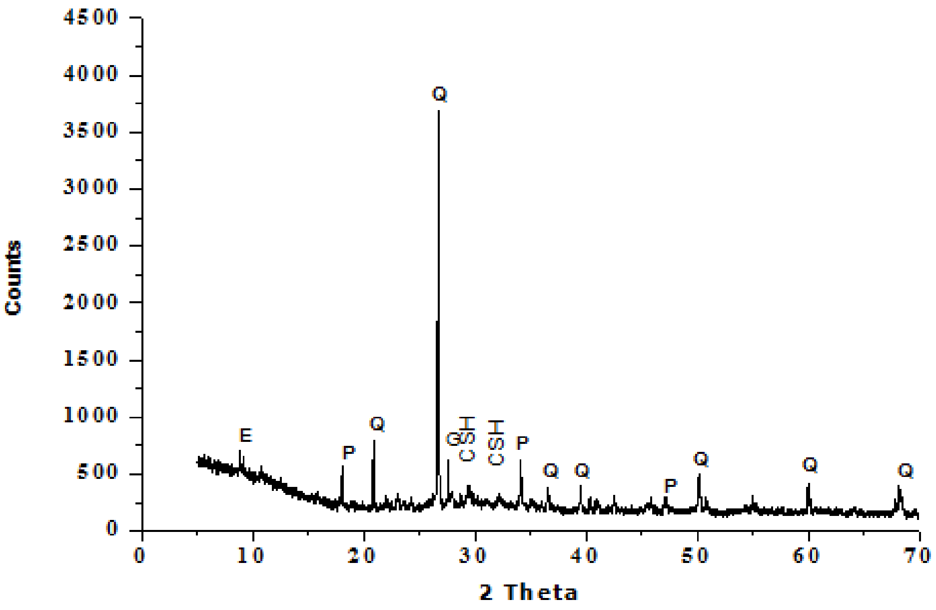

Figure 20. XRD spectrum of SF15 concrete cured in sulfate solution for 28 days after curing in water for 28 days (E is Ettringite, Q is Quartz, P is Porlandite, C is Calcite, CSH is Calcium silicate hydrate, G is Gismondine).

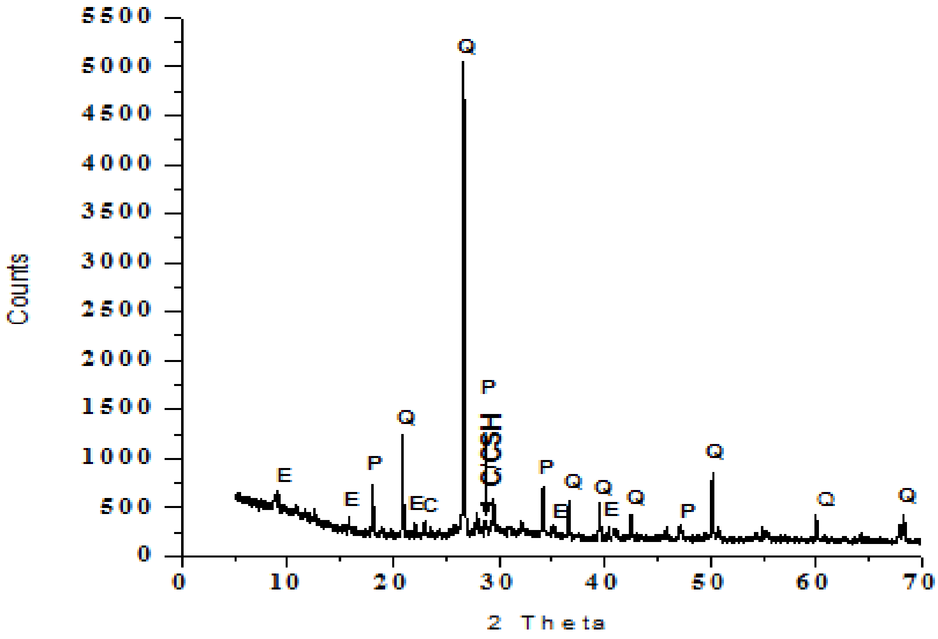

Figure 21. XRD spectrum of control concrete at 56 (28+28) days of water curing (E is Ettringite, Q is Quartz, P is Porlandite, C is Calcite, CSH is Calcium silicate hydrate, G is Gismondine).

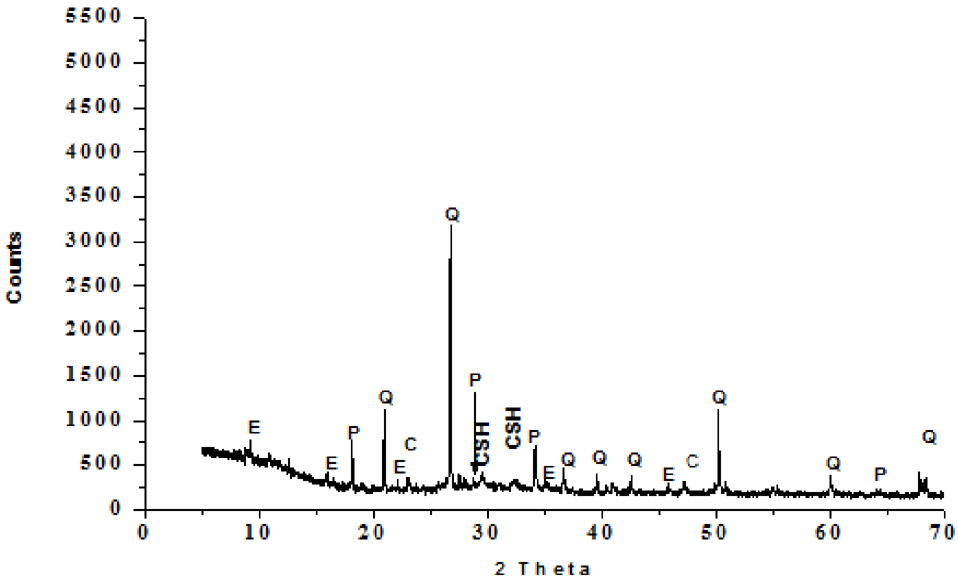

Figure 22. XRD spectrum of SF15 concrete at 56 (28+28) days of water curing (E is Ettringite, Q is Quartz, P is Porlandite, C is Calcite, CSH is Calcium silicate hydrate, G is Gismondine).

4. Conclusion

1. At all ages very slight change can be noticed in compressive strength values of control concrete and concrete containing maximum up to 20 % of waste foundry sand. As per results concrete containing 15 % waste foundry sand shows optimum results. Concrete mixtures cured in sulfate solution showed lower compressive strength compared to that of corresponding water cured concrete mixture at the same age.

2. Charge passing ability of water cured concrete mixtures reduces with the use of waste foundry sand at all the ages of curing. Concrete mixtures cured in sulfate solution displayed improvement in resistance against chloride ion penetration corresponding to water cured concrete mixtures at the same age.

3. No noteworthy variation in the ultrasonic pulse velocity of cured concrete mixtures in both water and sulfate solutions were observed.

4. Expansion of concrete mixtures cured in sulfate solution up to 56 days was greater than that of corresponding normal water cured concrete mixtures.

5. The Energy Dispersive Spectroscopy analysis validates the presence of sulfate ions in the concrete after immersion in a sulfate solution.

References

1. Carnin, R.L.P., Folgueras, M.V., Luvizão, R.R., Correia, S.L., da Cunha, C.J., Dungan, R.S. Use of an integrated approach to characterize the physicochemical properties of foundry green sands. Thermochimica Acta. 2012. 543. Pp. 150–155. DOI: 10.1016/j.tca.2012.05.018
2. Khatib, J.M., Ellis, D.J. Mechanical Properties of Concrete Containing Foundry Sand. ACI Special Publication. 2001. 200. Pp. 733–748.
3. Siddique, R., Aggarwal, Y., Aggarwal, P., Kadri, E.-H., Bennacer, R. Strength, durability, and micro-structural properties of concrete made with used-foundry sand (UFS). Construction and Building Materials. 2011. 25 (4). Pp. 1916–1925. DOI: 10.1016/j.conbuildmat.2010.1.065
4. Guney, Y., Sari, Y.D., Yalcin, M., Tuncan, A., Donmez, S. Re-usage of waste foundry sand in high-strength concrete. Waste Management. 2010. 30(8–9). Pp. 1705–1713. DOI: 10.1016/j.wasman.2010.02.018
5. Naik, T.R., Patel, V.M., Parikh, D.M., Tharaniyil, M.P. Utilization of Used Foundry Sand in Concrete. Journal of Materials in Civil Engineering. 1994. 6 (2). Pp. 254–263. DOI: 10.1061/(ASCE)0899-1561(1994)6:2(254)
6. Basar, H.M., Deveci Aksoy, N. The effect of waste foundry sand (WFS) as partial replacement of sand on the mechanical, leaching and micro-structural characteristics of ready-mixed concrete. Construction and Building Materials. 2012. 35. Pp. 508–515. DOI: 10.1016/j.conbuildmat.2012.04.078
7. Ganesh Prabhu, G., Hyun, J.H., Kim, Y.Y. Effects of foundry sand as a fine aggregate in concrete production. Construction and Building Materials. 2014. 70. Pp. 514–521. DOI: 10.1016/j.conbuildmat.2014.07.070
8. Ganesh Prabhu, G., Bang, J.W., Lee, B.J., Hyun, J.H., Kim, Y.Y. Mechanical and Durability Properties of Concrete Made with Used Foundry Sand as Fine Aggregate. Advances in Materials Science and Engineering. 2015. 2015. Pp. 1–11. DOI: 10.1155/2015/161753

9. Torres, A., Bartlett, L., Pilgrim, C. Effect of foundry waste on the mechanical properties of Portland Cement Concrete. Construction and Building Materials. 2017. 135. Pp. 674–681. DOI: 10.1016/j.conbuildmat.2017.01.028
10. Mastella, M.A., Gislon, E.S., Pelisser, F., Ricken, C., Silva, L. da, Angioletto, E., Montedo, O.R.K. Mechanical and toxicological evaluation of concrete artifacts containing waste foundry sand. Waste Management. 2014. 34 (8). Pp. 1495–1500. DOI: 10.1016/j.wasman.2014.02.001
11. Etxeberria, M., Pacheco, C., Meneses, J.M., Berridi, I. Properties of concrete using metallurgical industrial by-products as aggregates. Construction and Building Materials. 2010. 24 (9). Pp. 1594–1600. DOI: 10.1016/j.conbuildmat.2010.02.034
12. Singh, G., Siddique, R. Effect of waste foundry sand (WFS) as partial replacement of sand on the strength, ultrasonic pulse velocity and permeability of concrete. Construction and Building Materials. 2012. 26 (1). Pp. 416–422. DOI: 10.1016/j.conbuildmat.2011.06.041
13. Kaur, G., Siddique, R., Rajor, A. Influence of Fungus on Properties of Concrete Made with Waste Foundry Sand. Journal of Materials in Civil Engineering. 2013. 25 (4). Pp. 484–490. DOI: 10.1061/(ASCE)MT.1943-5533.0000521
14. Siddique, R., Singh, G., Singh, M. Recycle option for metallurgical by-product (Spent Foundry Sand) in green concrete for sustainable construction. Journal of Cleaner Production. 2018. 172. Pp. 1111–1120. DOI: 10.1016/j.jclepro.2017.10.255
15. Siddique, R., Schutter, G. de, Noumowe, A. Effect of used-foundry sand on the mechanical properties of concrete. Construction and Building Materials. 2009. 23 (2). Pp. 976–980. DOI: 10.1016/j.conbuildmat.2008.05.005
16. Siddique, R., Sandhu, R.K. Properties of Self-Compacting Concrete Incorporating Waste Foundry Sand. Leonardo Journal of Sciences. 2013. 12 (23). Pp. 105–124. U
17. Thaarrini, J., Ramasamy, V. Properties of Foundry Sand, Ground Granulated Blast Furnace Slag and Bottom Ash Based Geopolymers under Ambient Conditions. Periodica Polytechnica Civil Engineering. 2016. 60 (2). Pp. 159–168. DOI: 10.3311/PPci.8014
18. Smarzewski, P., Barnat-Hunek, D. Mechanical and durability related properties of high performance concrete made with coal cinder and waste foundry sand. Construction and Building Materials. 2016. 121. Pp. 9–17. DOI: 10.1016/j.conbuildmat.2016.05.148.
19. ASTM C1202-12. Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration. ASTM International, West Conshohocken, PA, 2012.
20. ASTM C1012 / C1012M-10. Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution. ASTM International, West Conshohocken, PA, 2010.
21. ASTM C597-02. Standard Test Method for Pulse Velocity Through Concrete. ASTM International, West Conshohocken, PA, 2002.
22. Divet, L., Randriambololona, R. Delayed Ettringite Formation: The Effect of Temperature and Basicity on the Interaction of Sulphate and C-S-H Phase 11Communicated by M. Moranville-Regourd. Cement and Concrete Research. 1998. 28 (3). Pp. 357–363. DOI: 10.1016/S0008-8846(98)00006-4
23. Tzouvalas, G., Rantis, G., Tsimas, S. Alternative calcium-sulfate-bearing materials as cement retarders: Part II. FGD gypsum. Cement and Concrete Research. 2004. 34 (11). Pp. 2119–2125. DOI: 10.1016/j.cemconres.2004.03.021
24. Fall, M., Pokharel, M. Coupled effects of sulphate and temperature on the strength development of cemented tailings backfills: Portland cement-paste backfill. Cement and Concrete Composites. 2010. 32 (10). Pp. 819–828. DOI: 10.1016/j.cemconcomp.2010.08.002
25. Gurumoorthy, N., Arunachalam, K. Micro and mechanical behaviour of Treated Used Foundry Sand concrete. Construction and Building Materials. 2016. 123. Pp. 184–190. DOI: 10.1016/j.conbuildmat.2016.06.143.

Information about authors:

Jagdeep Singh,
ORCID: https://orcid.org/0000-0002-4966-9894
E-mail: jagdeep.singh71717@gmail.com

***Rafat Siddique**, PhD*
ORCID: https://orcid.org/0000-0003-0128-6306
E-mail: siddique_66@yahoo.com

Received 03.07.2020. Approved after reviewing 28.09.2022. Accepted 09.11.2022.