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Experimental study on alkali-activated concrete using waste iron chips as partial replacement to fine aggregates

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Abstract

Alkali-activated concrete is essentially cement-free concrete resulting from the reaction of source material rich in silica and alumina with an alkaline liquid. This is being studied extensively and is considered a promising green substitute for ordinary Portland cement. The present study examines the properties of alkali-activated concrete mixes with waste iron chips (an industrial waste) in terms of their strength and durability. It is observed that all the mixes with the waste iron chips showed better strength characteristics compared to the reference concrete mix. Among all the mixes tested herein, mix with 20% waste iron chips had better strength characteristics. When these mixes are subjected to acid attack, their mass and strength decreased slightly, and when subjected to sulphate attack, no significant changes in mass and strengths are observed.

Keywords: Alkali-activated concrete, Waste iron chips, Strength, Durability, Density

1. Introduction

Concrete is used as a major construction material since it has unique characteristics such as strength, durability, flexibility etc. Moreover, it can be made from locally available materials as well. Ordinary Portland cement (OPC) is one of the major components used to make concrete, and to produce one ton of OPC, about one ton of CO_2 is released into the atmosphere. Hence, to overcome this problem, it is better to find alternate binder materials with similar strength and durability characteristics as that of OPC.

Many alternative binding materials such as Ground Granulated Blast-furnace Slag (GGBS), fly ash, silica fume, limestone fines and natural and artificial pozzolans have been successfully used in the past [1]. However, these binders can be used only as a part replacement to OPC.

Recently, alkali-activated concrete mixes have emerged as an alternative to OPC. These mixes require an alkaline solution, a mixture of sodium/potassium hydroxide and sodium silicate as an activator to form cementitious material. Alkali-activated concrete mixes are broadly classified into two types: Geopolymer concrete mixes and alkali-activated slag concrete mixes. The Geopolymer concrete mixes are fly ash-based mixtures and require heat curing for setting and attaining strength [2]. Such a curing method requires a large amount of heat energy, making it impractical for field applications.

On the other hand, GGBS based alkali-activated slag concrete mixes show promising strength and durability without using heat energy for curing. But they have a disadvantage of shorter initial and final setting times, making them difficult to use in the field again. Thus, to overcome these problems, recent works have suggested using a combination of slag and fly ash as a binder [3-4]. Though different results suggest different optimum dosages of fly ash and GGBS for better strength characteristics [5], a consensus on optimum dosage has not been reached yet. This may be due to the fact that the chemical composition of the fly ash and GGBS vary from place to place.

In the construction industry, usually, river sand is used as a fine aggregate. But due to surge in construction activities, demand for river sand is increasing day by day. As river sand is scarce and the quarrying of sand causes a huge impact on the environment, alternative materials that can serve as fine aggregate are being explored. Materials like manufactured sand (M-sand), slag sand, quarry dust, etc., are used. In addition to this, several materials such as waste products generated from industries have also been studied. These materials can be used to replace fine aggregate either completely or partially.

Every year millions of tons of waste are generated from several industries. Among them, some of the waste materials are recycled and utilized, but others remain unutilized, leading to environmental pollution [6]. There are many types of waste materials generated from industries. In the present study, waste iron chips obtained from iron fabrication industries are considered a fine aggregate replacement. Waste iron chips are essentially a combination of an angular, elongated, powder formed by-product with a density higher than M-sand. Past studies suggest that similar waste materials have been used for attaining good strength and durability characteristics [7]. Although studies on waste iron powder incorporated with OPC have been conducted, industrial wastes differ in composition and physical properties. Hence, separate studies are required for concrete mixes produced from these materials.

Alwaeli M, et al [8] observed that the concrete mixed with steel chips has better strength properties than conventional concrete. Whereas the strength decreased in the case of concrete mixed with scale in excess of 25%. Similarly, Ismail and Al-Hashmi [9] observed an increase in compressive and flexural strength by 17% and 28% (compared to the reference concrete) when 20% of sand was replaced with waste iron. Few reported works carried out on alkali-activated concrete mixes incorporated with waste/scrap iron chips. The present work aims to study the strength and durability behaviour of alkali-activated concrete mixes incorporated with waste iron chips.

2. Materials and methods

2.1 Materials

Fly ash is a fine material that mainly consists of reactive phases of Aluminum and Siliceous compounds that can be used as a binder that can partly replace OPC. In the present study, fly ash was procured from Messers (M/s) Raichur Thermal Power Corporation Limited (RTPCL), Shaktinagar, Raichur, and it conforms to the specifications of Indian Standard (IS):3812-2003 (class F) [10]. Its specific gravity was found to be 2.01. GGBS was procured from M/s Jindal Iron and Steel Works (JSW), Torangal, Karnataka, and conforms to the specifications of IS:12089- 2008 [11]. Its specific gravity was 2.85. Results of the chemical composition of fly ash and GGBS are presented in Table 1. Two types of fine aggregates have been used in this experimental study, and they are locally available M-sand and waste iron chips. The M-sand's specific gravity, bulk density, and water absorption were 2.4, 1850 kg/m^3 and 7% respectively.

Table 1 Chemical composition of fly ash and GGBS.

Parameters	Mass %	
	Fly ash	GGBS
SiO_2	62.0	37.730
Al_2O_3	22.0	14.420
Fe_2O_3	2.3	1.110
CaO	2.0	37.340
Loss of ignition	1.8	1.410
MgO	0.9	8.710
Insoluble Residue	0.5	1.590
MnO	-	0.002
SO_3	-	0.390
Glass content	-	92

Waste iron chips were collected from a fabrication factory in Peenya, Bangalore. The waste iron chips' specific gravity, bulk density, and water absorption were 5.9, 2178 kg/m^3 and 2%, respectively. A significant portion of raw waste iron chips samples was found to be elongated and flaky particles. To address this issue, Los Angeles abrasion testing machine was used to crush the sample and remove the elongated, flaky, and friable particles. The sample was placed in the Los Angeles abrasion testing machine for different rotations to remove the elongated and flaky particles. To optimize the number of rotations, five different rotations, namely 30, 60, 90, 120, and 150, were performed, and sieve analysis was carried out on the resulting material. It was observed that there was a variation in percentage passing up to 90 rotations, beyond that, there were no significant changes in the percentage passing. This means that most of the friable particles have been broken down at 90 number of rotations. Hence, it was decided to use the material after subjecting it to 90 rotations. Before and after processing, the waste iron chips are presented in Figures 1. The particle size distribution curve for M-sand and waste iron chips are shown in Figure 2.

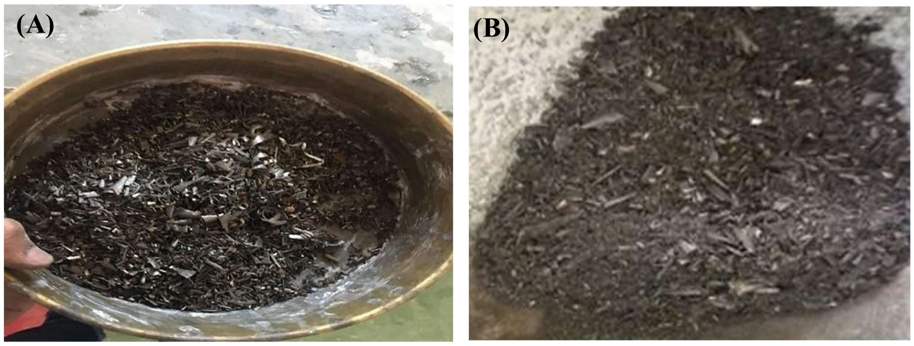

Figure 1 Waste iron chips (A) before (B) after the treatment.

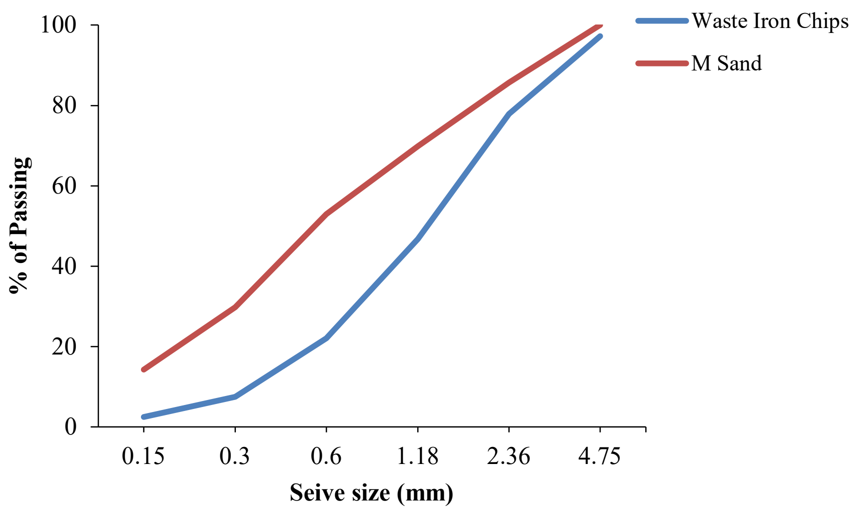

Figure 2 Particle size distribution curve for m-sand and waste iron chips.

Crushed angular granite aggregates with a maximum aggregate size of 12 mm were used as the coarse aggregates. The coarse aggregate is found to have a specific gravity of 2.5, bulk density 1610 kg/m^3 and water absorption of 1.01%.

Sodium silicate solution was procured from a local chemical factory whose modulus ratio was 2.7. Sodium hydroxide pellets were procured locally and based on the required molarity; the amount of water was added to prepare the solution. In this study, 14 M solution was used for making alkali-activated concrete mixes.

2.2 Mix proportions

Presently, there are no codal guidelines for proportioning alkali-activated concrete mixes, and hence the mixes are proportioned by trial mixes. The final mix proportions obtained after the trial mixes are shown in Table 2. A total of 6 mixes were prepared for varying dosages of waste iron chips. The M-sand is replaced in five proportions by using waste iron chips on a volume basis. The replacements considered are from 0-50% by volume of the M-sand.

Table 2 Mix proportions for different mixes.

Mix	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3) M- sand	Waste iron chips	Alkaline liquid / binder ratio	Binder materials Fly ash (kg/m^3)	GGBS (kg/m^3)	Na_2SiO_3/ NaOH	Na_2SiO_3 (kg/m^3)	NaOH solution (kg/m^3)
RC	837.7	973.6	0	0.45	265.2	142.8	2.5	131.1	52.4
WIC10	837.7	876.2	204.3	0.45	265.2	142.8	2.5	131.1	52.4
WIC20	837.7	778.9	408.7	0.45	265.2	142.8	2.5	131.1	52.4
WIC30	837.7	681.5	613.1	0.45	265.2	142.8	2.5	131.1	52.4
WIC40	837.7	584.1	817.5	0.45	265.2	142.8	2.5	131.1	52.4
WIC50	837.7	486.8	1021.9	0.45	265.2	142.8	2.5	131.1	52.4

RC: Reference mix.
WIC: Mixes incorporated with Waste Iron Chips.

2.3 Tests for fresh and hardened properties

Abram's slump cone test was used to measure the workability of all the mixes. Compression testing of cube specimens was carried out in a compression testing machine of capacity 2000 kN as per the guidelines of IS: 516-1959 [12]. The load was applied without shock at a rate of 140 kg/cm^2/min. A set of three cubes were tested for each of the mix for their compressive strengths at 7- days and 28- days of curing. Smaller-sized (of 100 mm sides) cubes have been used in the present investigation for testing the compressive strengths of the various mixes in view of material savings. Later the strengths obtained were multiplied with a correction factor found experimentally to determine the corresponding strengths of standard 150 mm cubes. Splitting tension tests are carried out, on standard cylindrical specimens for all the concrete mixes, as per the guidelines of IS: 5816-1999 [13]. Standard cylinders of size 150 mm diameter and 300 mm length are used for split tensile strength tests. Tests for measuring the modulus of elasticity of the various mixes were carried out on standard cylindrical specimens of 150 mm diameter and 300 mm length, as per the guidelines of IS:516-1959. The compression testing machine's loading rate was maintained at 140 kg/cm^2/min.

Apparent porosity indicates the amount of water absorbed by the concrete after 28 days of curing. The test is conducted as per American Society for Testing and Materials (ASTM): C20-00(2015) [14]. The cube specimen sample is oven dried for 24 h at 100°C and weighed and noted down as dry weight. The same sample is cooled to normal temperature and then immersed in water for 24 h. The wet weight was noted after the immersion period. The apparent porosity is calculated as,

$$\text{Apparent porosity} = \frac{\text{wet weight} - \text{dry weight}}{\text{dry weight}} \text{x} 100 \quad (1)$$

Modulus of elasticity is performed using cylinders having a diameter of 150 mm and 300 mm in height. The specimens were cast and cured for 28 days. Stress and strain values were calculated using the experimental data. The stress vs strain graph is plotted, and the modulus of elasticity value is obtained by taking the initial tangent modulus. This test was carried out as per the guidelines of IS 9221:2013 [15].

Test for acid resistance was conducted using sulphuric acid (H_2SO_4) for 28 days, as per the guidelines of ASTM: D6137-2018 [16]. Concrete cubes of size 100mm were cast and cured for 28 days. The initial densities of the concrete cubes were recorded. Then they are immersed in H_2SO_4 solution of pH =1. To maintain this pH, 10 mL of acid is added to 1 litre of solution on daily basis. After the immersion period of 8 days, the residual density and compressive strength were recorded.

Similarly, to study the performance of concrete mixes against the sulphate attack, tests are conducted as per the guidelines of ASTM: C1012-2015 [17]. Concrete cube specimens of size 100mm were cast and cured for 28 days. The specimens were tested for sulphate attack using 5% sodium sulphate and 5% magnesium sulphate solution for an immersion period of 28 days. The pH of the solution was maintained between 6-8.

There are unknown hydration phases present in the mixes because of the combination of fly ash and GGBS as the binder material. To perform material characterization and to identify the hydration phases in alkali-activated concrete mixes, X-ray diffraction (XRD) test was conducted. The sample paste of alkali-activated mix, consisting of fly ash and GGBS along with the alkaline solution, is separately cast in a small plastic mould and cured for 28 days. Later, it was immersed in glycerine to cease hydration till the time of testing.

3. Results and discussion

3.1 Tests on fresh concrete

A slump cone test was conducted to measure the workability of the fresh concrete mixes. It is observed that with the increasing percentage of waste iron chips, the slump value tends to decrease (Figure 3). It is due to the fact that the fineness of the waste iron chips is lower than the M-sand, and hence more amount of water is consumed to wet the surfaces of these particles. The reduction in the slump was found to be about 55% for 50% replacement of M-sand by waste iron chips.

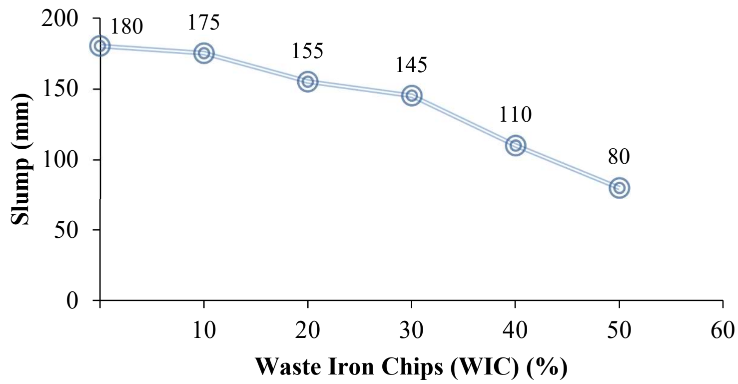

Figure 3 Slump vs % Waste iron chips.

3.2 Tests conducted on hardened concrete

3.2.1 Compressive strength

In general, all the mixes with waste iron chips showed higher strength properties as compared to the reference mix (Figure 4). It is observed that there is an increase in compressive strength at both 7 and 28-days. This phenomenon of increasing strength is found till 20% replacement, after which there was a gradual decrease. The reference mix achieved a 28-day compressive strength of 35.3 megapascals (MPa). Among all the WIC mixes, the maximum strength of 53.1 MPa is achieved for WIC mix with 20% waste iron chips, and the minimum strength of 38 MPa is observed for WIC mix with 10% waste iron chips. At the age of 28 days, all mixes showed higher compressive strength compared to the reference mix. The percentage increase in strengths for 10, 20, 30, 40, and 50% replacement of M-sand by waste iron chips are found to be about 7.6, 50.4, 38.8, 22.9, and 19.8%, respectively. It is also observed that the density of mixes increased with an increasing percentage of iron chips, which is because the waste iron chips have greater specific gravity than M-sand. The optimum dosage with respect to strength characteristics is 20% replacement. Since the waste iron chips are irregular in shape, as shown in Figure 1, their increased replacement does not guarantee minimum voids and maximum density. Among all the percentage dosages, the combined aggregates attain minimum voids content at 20% replacement and hence have shown maximum strength characteristics.

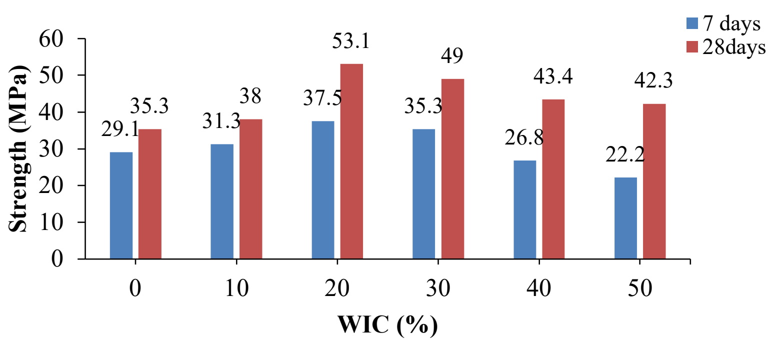

Figure 4 Compressive strength of all the mixes.

3.2.2 Split tensile strength

The split tensile strengths showed a similar trend of strength characteristics as that of compressive strength (Figure 5). There was a considerable increase in split tensile strength up to 20% replacement of waste iron chips, after which a decreasing trend is observed. In all the cases, the split tensile strengths are higher than the reference concrete mix. The maximum tensile strength is observed for the WIC mix with 20% replacement.

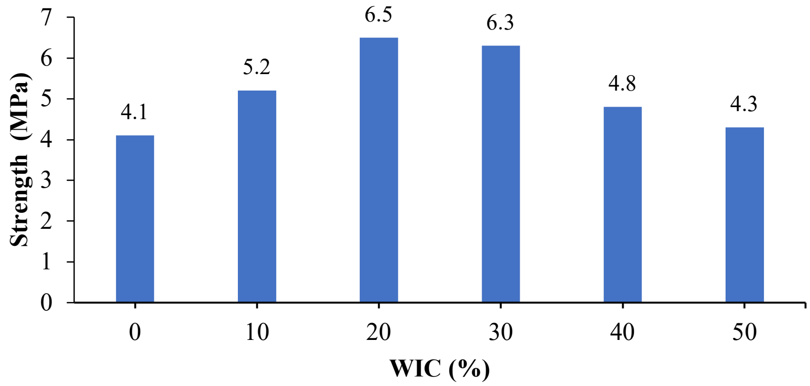

Figure 5 Split tensile strength of all the mixes.

3.2.2 Apparent porosity

The results of the apparent porosity tests are presented in Figure 6. It is observed that the specimen with the 20% iron chips absorbed less water compared to all the other mixes. Overall, it is found that the variations in apparent porosity values of the WIC mixes are insignificant. The minimum apparent porosity of the mix with 20% iron chips indicates a lower void ratio and hence lower apparent porosity.

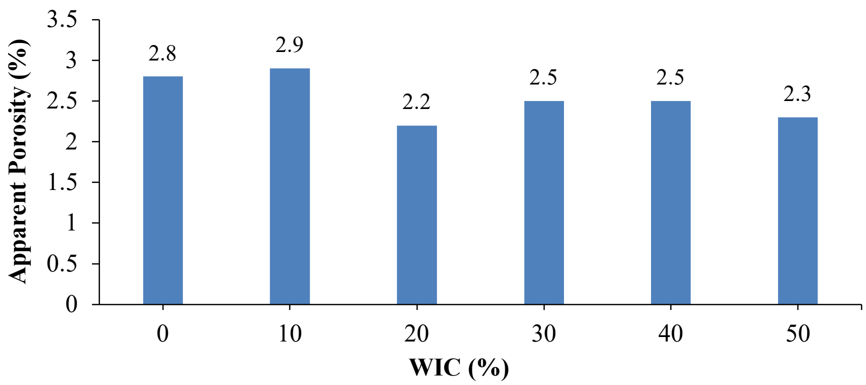

Figure 6 Apparent porosity of all the mixes.

3.2.3 Modulus of elasticity

It is observed that the moduli of elasticity of all the mixes are found to be significantly higher than that of the control concrete mix (Table 3). This is because the mixes with higher densities will always result in a higher modulus of elasticity. The modulus of elasticity of a mix with 20% iron chips is about 42.4 gigapascal (GPa), which is about 49.8% higher than that of the control concrete mix. Among the WIC mixes, mix with 20% waste iron chips had a comparatively higher modulus of elasticity, which may be due to lower porosity as compared to the other mixes (Figure 6).

Table 3 Modulus of elasticity of all the mixes.

Mix	Compressive strength (MPa)	Modulus of elasticity (GPa)	% Increase
RC	31.8	28.3	0.0
WIC10	34.2	30.8	8.8
WIC20	47.8	42.4	49.8
WIC30	44.1	37.4	32.2
WIC40	39.0	38.2	35.0
WIC50	38.1	37.4	32.2

3.3 Tests conducted on durability

3.3.1 Acid attack test

The changes in the density of the mixes before and after exposure to acid for 28 days are presented in Figure 7. In general, it is observed that there is a decrease in the density for all the types of mixes after the exposure to acid attack. The changes in the density of the specimens after an exposure of 28 days are negligible. A maximum mass loss of about 2% is observed for the WIC 30 mix. The reduction in density is mainly due to the mass loss of the waste iron chips, which started disintegrating due to corrosion. The specimens subjected to acid attack showed a layer of corrosion product in the form of powder on the surface of the specimens, as seen in Figure 8. The sulphuric acid reacts with iron chips to form the corrosion product, i.e., ferrous sulphate and this is exhibited as rust on the surface of the cubes.

The samples were tested for compressive strength after they were exposed to acid attack. Figure 9 presents the results of the tests. It is observed that the compressive strength tends to decrease after 28 days of acid attack irrespective of the replacement level. The maximum percentage of strength loss was observed at 20% replacement of iron chips which is around 21%.

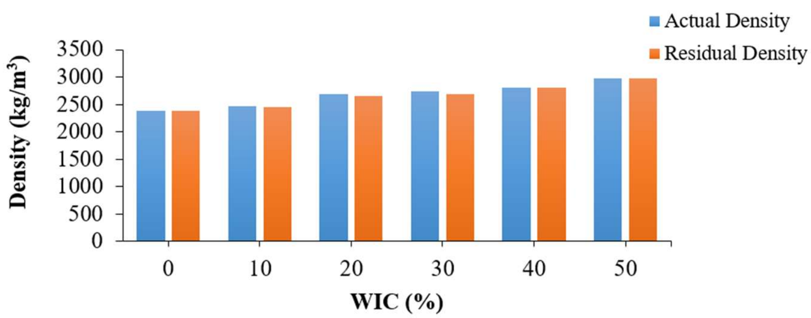

Figure 7 Density before and after acid attack of all the mixes.

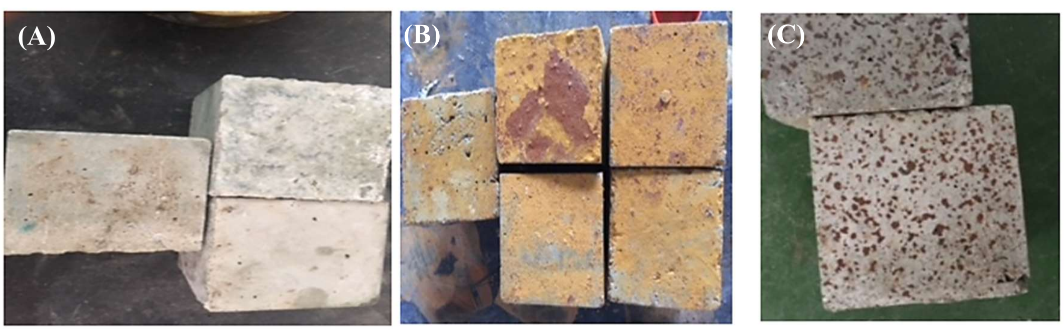

Figure 8 Cube specimens (A) exposed to acid (B), and sodium sulphate (C).

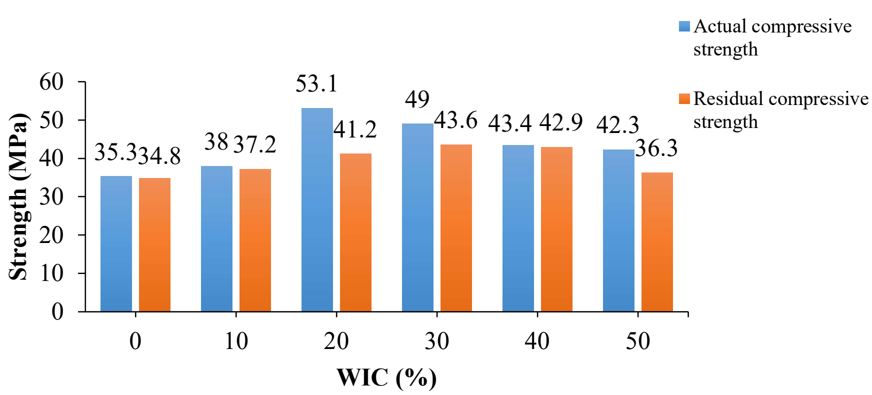

Figure 9 Comparison of compressive strength.

3.3.2 Sulphate attack test

It is observed that there is an increase in the density of the specimens for exposure to both sodium and magnesium sulphates (Figure 10). The compressive strength was also found to increase for exposure to both sodium and magnesium sulphates. This increase in density and compressive strength occurs because sulphates in solution enter into the pores present in the cubes, settle there and form gypsum, which leads to the expansion of concrete [18]. In general, it is found that when the WIC mixes with waste iron chips were exposed to sulphate attacks, a corrosion tendency of the exposed particles was seen (Figure 8C). The specimens exposed to sulphate attack showed the corroded waste iron particles on the surface. Through detailed studies on the nature of corrosion and the type of corrosion products that have not been conducted here, careful observations of these exposed specimens indicate that the use of waste iron chips in Alkali-activated concrete mixes may not be feasible as it would attract corrosion attack when exposed to acid or sulphate environments.

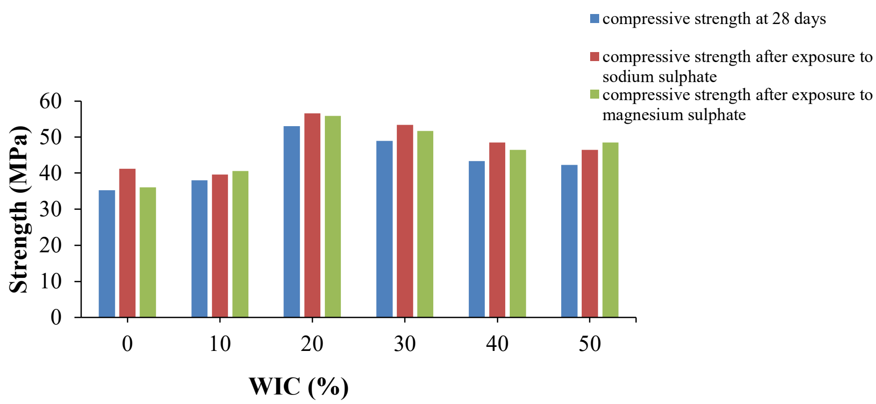

Figure 10 Comparison of compressive strength before and after sulphate attack.

3.3.3 Hydration products

An X-ray diffraction test was conducted to perform material characterization and identify the hydration phases present in the alkali-activated concrete mixes. The data obtained from this test was analysed using a standard analysis tool. The XRD analysis was carried out for a sample with a combination of 35% of GGBS and 65% of fly ash as the binder material, and the major hydration phases are detailed below in Figure 11. The hydration phases indicated the presence of Wairakite, Mullite, Albite and Quartz (Table 4).

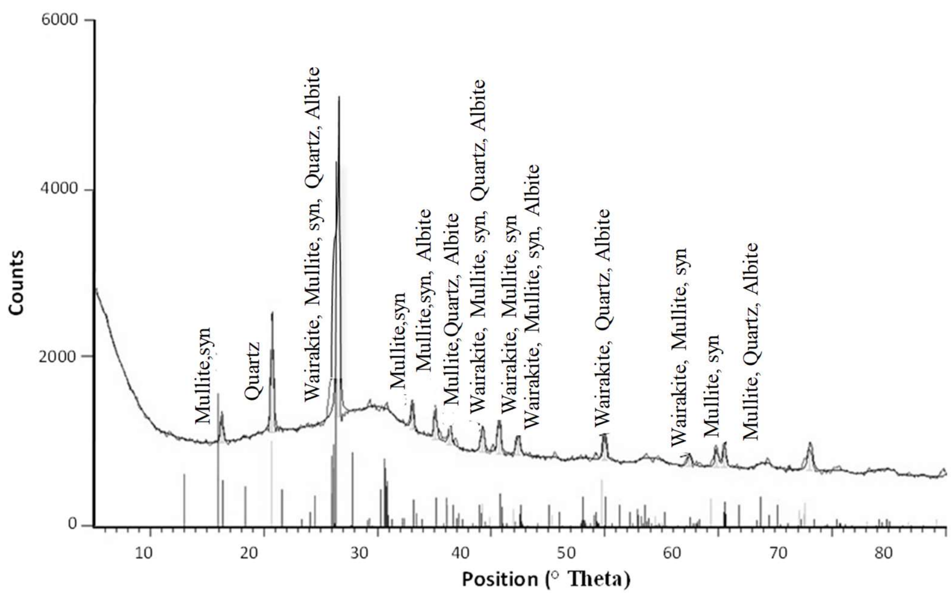

Figure 11 Major hydration phases detected.

Table 4 Hydration phases with molecular formula.

Compounds	Molecular formula
Wairakite	$Ca(Al_2Si_4O_{12})\cdot 2H^2O$
Mullite	$3Al_2O_3.2SiO_2$
Quartz	SiO_2
Albite	$Na2O.Al2O_3.6Si3O2$

4. Conclusion

The present experimental investigation observed that the workability of mixes tends to decrease with an increase in the percentage of waste iron chips. In general, the concrete mixes with waste iron chips showed higher strength characteristics as compared to the reference mix. The reference mix attained a 28-day strength of 35.3 MPa, while the WIC20 mix, with 20% waste iron chips, attained about 50.4% higher strength of 53.1 MPa (Max.) among all the WIC mixes. Similarly, the split tensile strength showed an increasing trend up to 20% replacement of waste iron chips and later showed decreasing trend. Modulus of elasticity for the mixes with iron chips is found to be significantly higher than that of the reference mix and varied from 25 to 45 GPa. The maximum elasticity observed at the 20% replacement was 42.4 GPa. Concrete exposed to acid attack shows a slight decrease in compressive strength and mass loss with the increase in waste iron chips. There was a slight increase in density and compressive strength with increasing dosages of waste iron chips after exposure to sulphate attack. The apparent porosity of mixes attained was about 2%, which indicates that the alkali-activated mixes with iron chips do not absorb a significant amount of water. The hydration phases of the alkali-activated concrete mix with 35% GGBS and 65% fly ash indicated the presence of Wairakite, Mullite, Albite and Quartz.

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