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Research paper

Investigation of concrete produced using recycled aluminium dross for hot weather concreting conditions

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Abstract

Aluminium dross is a by-product obtained from the aluminium smelting process. Currently, this dross is processed in rotary kilns to recover the residual aluminium, and the resultant salt cake is sent to landfills. The present study investigates the utilization of recycled aluminium dross in producing concrete, which is suitable for hot weather concreting condition. The primary objectives of the experimental study are to examine the feasibility of using concrete blended with recycled aluminium dross under hot weather concreting situations and then to evaluate the strength and durability aspects of the produced concrete. From the experimental results it is observed that the initial setting time of the recycled aluminium dross concrete extended by about 30 minutes at 20% replacement level. This property of recycled aluminium dross concrete renders it to be suitable for hot weather concreting conditions. Based on the results obtained, the replacement of cement with 20% of Al dross yields superior mechanical and durability characteristics.

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Keywords: Hot weather concrete; Recycled aluminium dross; Durability of concrete

1. Introduction

The hot weather is considered to be any combination of high air temperature, low relative humidity and increased wind velocity [1]. Concrete applications may be considered as hot weather concrete at temperatures above 40 °C depending on the site specific application as per IS:7861 (Part 1)-1975 [2]. The actual temperature of the concrete mix as conveyed to the site is effected by the temperature of the ingredient materials used in the mix, the temperature of the equipment used to batch and transport the concrete, the cementitious content of the mixture, and finally by the ambient temperature and conditions at the project site. Ideal conditions for placing concrete occur when temperature ranges between 68 °F and 72 °F (20 °C and 22 °C), the relative humidity is 50 percent or higher and the near surface wind velocity is low [3]. As a general rule of thumb, an increase of 20 °F will reduce the setting time of a concrete mixture by as much as 50 percent [4]. Some of the effects of hot weather concreting include accelerated setting time of concrete; increased tendency for plastic shrinkage; potential strength reduction due to high water demand and high curing temperatures; and stiffening of the mix prematurely, preventing it from being well compacted and finished properly.

Nowadays, there is an intense need to come out with novel technologies to convert various wastes into serviceable feedstock cost-effectively. Currently, various kinds of pozzolanic materials are blended along with cement during the production of concrete for modifying the strength and durability properties of conventional concrete. Indeed, the use of pozzolanic materials existed before the discovery of contemporary ordinary Portland cement (OPC) nearly about 2000 years ago itself [5]. Most of the pozzolanic materials are nothing but the by-products procured from industries, for instance, coal fly ash, blast furnace slag, rice husk ash, silica fume, etc. Intrinsically, there has been not much research done with respect to manufacturing, engineered and optimized pozzolanic materials, which are purposely explored for usage along with Portland cement.

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Aluminium dross is a by-product obtained from the aluminium smelting process. Currently, this dross is processed in rotary kilns to recover the residual Al, and the resultant salt cake is sent to landfills. The composition of recycled aluminium dross is typically variable and unique to the plant generating the waste [6]. The recycled aluminium dross contains some volume fraction of toxic materials and land filling of these toxic substances is not ecologically fair. So, in the present study an effort has been put forth to utilize recycled aluminium dross as an admixture, while producing concrete suitable for hot weather concreting conditions.

There are relatively few successful applications employing recycled aluminium dross in concrete technology. Puertas et al. [7] researched on using PAVAL™ (a high alumina content waste) generated from aluminium refining industries for application as a partial replacement of fine aggregates in producing cement mortar. Their main finding was that the PAVAL™ waste had a high specific surface area which resulted in requirement of higher quantity of mixing water. They also observed that there was a considerable increase of the total porosity and decrease of the mechanical strengths when compared to that of conventional silica sand mortar. The aluminium dross was found to retard the hydration reactions in cement mortar during the calorimetric study. The initial and final setting time was found to be extended for more than 2 hours. On the other hand, a decrease in the average size of the pores was seen, which had a progressive influence on the durability characteristics of the final material. Ewais et al. [8] investigated on calcium aluminate cement mixes. They used both aluminium sludge and aluminium slag in their study. Aluminium sludge was the source of both CaO and Al_2O_3 whilst the aluminium slag had only aluminium oxide with certain supplements of pure alumina. The cement mixes manufactured from 37.50 to 41.25% of aluminium slag (dross), 45–50% of aluminium sludge and 12.50–13.75% of alumina were observed to be the ideal mix for manufacturing calcium aluminate cement. Elinwa and Mbadike [9] examined the applicability of using aluminium wastes to manufacture concrete samples. They carried out tests on the setting time, flexural and compressive strengths at 5, 10, 20, 30 and 40% cement replacement levels. They conclude that under hot weather concreting, the aluminium wastes serve as a retarder. The optimum substitution level for the better flexural and compressive strengths was found to be at 10% by weight of cement. Arimanwa et al. [10] examined the characteristics of concrete produced using aluminium waste (an auxiliary cementitious element) and proposed a prediction model based on Scheffe's theory for the prediction of the compressive strength of aluminium waste-cement concrete. The residue produced from aluminium extrusion plants was employed as a partial substitute for cement in different mix ratios. The initial and final setting times of concrete decreased due to the addition of aluminium waste. The partial replacement of cement with aluminium waste did not modify the density of the resulting concrete significantly. One of the important findings was that the aluminium waste absorbed water from the design mix and thereby degraded the workability of the concrete. Mbadike [11] reports the influence of integration of aluminium waste for producing concrete matrix of diverse water-to-cementitious ratio and mix proportions. By varying water to cement ratio, cubes of various mix proportions were cast. The 7, 14 and 28 days strength of the cube samples were tested. A standard 1:2:4:0.55 mix with 5% aluminium waste resulted in an increase of compression strength from 26.07 N/mm^2 to 28.47 N/mm^2, thereby exhibiting a rise of 9.21% of the compressive strength. For 1:2:4 mix proportion of aluminium waste concrete, the slump of concrete ranged from 4 to 20 mm, while that for 1:3:6 mix proportion ranged from 7 to 14 mm.

Weather conditions can have a remarkable influence on the setting time, concrete placing and finishing. Hot weather concrete problems normally arise during the period of the summer season. Thermal shrinkage is more critical during autumn and spring (temperature differential) [12]. It is highly significant to study the consequences of the environmental factors which impact over the characteristics of fresh and hardened concrete and thereby formulate precautionary measures needed to prevent the damages occurring to the concrete. In hot weather concreting, with the use of conventional concrete, the water content present in it evaporates at a faster rate, thereby accelerating the initial and final setting times [13]. Since the concrete produced using aluminium wastes retards the initial and final setting times, it proves to be beneficial under hot weather concreting conditions. Additionally the aluminium waste serves as a supplementary cementitious material and can be substituted with cement.

Due to hot weather conditions, problems arise in mixing, placing, and curing of concrete, which invariably affect the durability and serviceability properties of the concrete. The reason for these problems may be the increased hydration rate of concrete and evaporation of moisture from fresh concrete. The factors which affect the hydration rate of concrete are its on-site temperature, composition, cement fineness and the type of admixtures employed. Since India is a tropical country and most of the regions here lie in the tropical zone, it is necessary for engineers to be aware of tackling problems encountered during production and placement of concrete in hot weather conditions. Hence the main objective of the present study is to examine the feasibility of using recycled aluminium dross in concrete as a partial replacement to cement and evaluating its strength and durability aspects under hot weather conditions. The properties of concrete like compressive, tensile and flexural strengths are investigated for recycled aluminium dross concrete mixes that are produced under hot weather conditions. Additionally, durability properties like water absorption and acid resistance of recycled aluminium dross concrete are tested.

2. Materials and methodology

CEMENT: In ordinary Portland cement (OPC), more or less 3/4th of the mixture is one or the other forms of calcium silicate which is responsible for the bonding/gluing process. The OPC when mixed with water undergoes chemical reaction leading to the solidification of the cement material and this process is the so-called "hydration of cement". Some of the vital aspects/properties, which play an active role in the choice

Table 1
Chemical composition of cement and aluminium dross.

Composition of cement		Composition of aluminium dross	
Element	Percentage by weight	Element	Percentage by weight
Silicon di oxide (SiO_2)	17–25%	MgO	0.45
Ferric trioxide (Fe_2O_3)	0.5–0.6%	Fe_2O_3	0.32
Aluminium tri-oxide (Al_2O_3)	4–8%	CaO	20.2
Calcium oxide (CaO)	61–63%	Al_2O_3	63.29
Sulphur tri-oxide (SO_3)	1.3–3%	SiO_2	6.36
Magnesium oxide (MgO)	0.1–4%	Na_2O	0.36
Sodium oxide + Potassium oxide, (Na_2O+ K_2O)	0.4–1.3%	ZnO	0.93
Chlorine (Cl)	0.01–0.1%	MnO	0.73
Others	0.6–1.8%	LOI	5.3

Note: Remaining 2.06% of composition of Al dross is credited by traces of TiO_2, CuO, CdO, S, K and P.
TiO_2, Mn_2O_3 and N_2O are present in traces in the cement composition also.
LOI, loss on ignition.

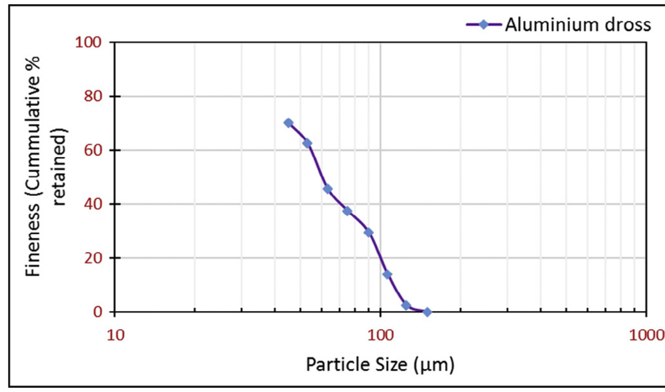


Fig. 1. Particle size distribution of aluminium dross sample.

of cement are its fineness, compressive strength at different ages, heat of hydration, Tri calcium aluminate (C_3A) content, Di calcium silicate (C_2S) content, Tri calcium silicate (C_3S) content and degree of alkali content. It is also mandatory to test the compatibility of the mineral and chemical admixtures with the cement. For the present investigation, 'ACC' (brand name) 53 grade OPC conforming to IS: 12269-1987 [14] is used. The chemical composition of the cement as provided by the manufacturer is presented in Table 1.

AGGREGATES: The natural river sand which is easily accessible nearby is used as fine aggregate (FA) in the present study. Its shape is of cubical or rounded in nature with a smooth surface texture, ensuring a good workability of concrete. The sand is procured from the nearby Karur River. Crushed granite with a maximum nominal size of 20 mm of somewhat cubical, round and angular in shape, with an aggregate crushing value <45%, is used as coarse aggregate in the present study. Both the fine and coarse aggregates were separated into different size fractions and recombined to a specific grading. The fine and coarse aggregates each had a specific gravity of 2.448 and 2.798; and water absorptions of 0.40 and 0.25%, respectively. Both the coarse and fine aggregate properties conform to IS: 383–1970 [15] standard.

ADMIXTURE: Admixtures are employed when a specific performance, such as an increase in strength, improved durability, reduction in water demand, low heat of hydration, impermeability and so on are needed. They also result in energy and cost savings. Materials such as fly-ash, blast furnace slag, silica fume, aluminium dross and so on can be effectively used as admixtures with cement, to modify and up grade the rheological properties of concrete. In the present study, concrete is produced by blending aluminium dross with cement at different proportions. The aluminium dross admixture is utilized as a retarder in order to manufacture concrete suitable for hot weather concreting. Aluminium dross was obtained from *Castle Engineering Works*, Coimbatore. The dross used for the experimentation was the white dross which possessed lower salt content. The dross had an egg odour. The collected dross was finely powdered using an impact pulverizer and sieved with 150 µm IS sieve size to obtain a finely crushed (powdered) material which was then used in the production of concrete. The specific gravity of the respective dross is 3.39. The sieves conforming to IS: 460-1962 [16] were used to carry out the standard "Particle size analysis" test in order to determine the relative proportions of different grain sizes distributed among certain size ranges. The particle sizes in Al dross vary from less than 45 µm up to 150 µm with the typical particle size measuring under 90 µm. Only about 30% of the particles by mass were larger than 90 µm. The results of particle size analysis are plotted on linear/logarithmic coordinates (see Fig. 1). The specific surface area is about 375 m^2/kg. The cement used in the present study had a specific surface area of 330 m^2/kg. The specific surface area of Al dross is comparatively higher than that of cement and has a direct influence on the pozzolanic reaction. The Al dross functions as a filler material to seal the voids present in the mix and also aids in the strength development of concrete. The percentage of constituents in the respective dross are tabulated in Table 1. IS: 9103-1999 [17] specifies that whenever any retarder is used, the minimum compressive and flexural strength should be 90 percent of the control sample at 28 days.

The aluminium dross causes a delay in the setting time of concrete by one or more mechanisms. It adsorbs over the surface of cement particles and acts as a diffusion barrier, thereby developing a shielding covering which decelerates the hydration process. It also adsorbs over the nuclei of calcium hydroxide $Ca(OH)_2$, thereby reducing its intensification, which is mandatory for continued hydration of cement. The inorganic salts present in the aluminium dross (for e.g., the metal oxides) form insoluble hydroxides in alkaline solution and suppress the cement hydration by forming a protective coating over the cement grains.

2.1. Proportioning of concrete materials

For hot weather concreting conditions, slight variations in material proportions should be made in order to arrive at the required properties of concrete mix; the mixing speed of the mixer must be apprehended to a minimum so that it allows for the escape of any excessive heat gain during production of

Table 2
Mix proportion of trial mixes.

Mix designation	M1	M2	M3	M4	M5	M6	M7	M8
Cement content (kg/m^3)	425.73	383.16	340.59	298.02	478.95	431.05	383.15	335.25
Fine aggregates (kg/m^3)	626.31	626.31	626.31	626.31	610.48	610.48	610.48	610.48
Coarse aggregates (kg/m^3)	1167.49	1167.49	1167.49	1167.49	1138	1138	1138	1138
Al dross (%)	0	10	20	30	0	10	20	30
Al dross (kg/m^3)	0	42.57	85.14	127.71	0	47.9	95.8	143.7
w/b ratio	0.45	0.45	0.45	0.45	0.4	0.4	0.4	0.4

concrete. While the concrete is fresh, it should possess adequate workability so that it will be easier to place it in the formwork economically [1]. The purpose of mix proportioning is to achieve a product that will meet the quality requirements according to certain standard code provisions; the most vital requirements being the workability of fresh concrete, durability and strength aspects of hardened concrete. It is in contrast, known that specific relationships exist between the properties of cement concrete and the individual effects of water to cement ratio, aggregate particle shape, aggregate to cement ratio and grading of aggregates. Hence, concrete mix design is not a science, but rather an art, of combining various materials for achieving required special properties.

As per IS 10262-1982 [18], a nominal concrete mix is designed in order to produce an M30[1] grade concrete. The binder to aggregate ratio[2] is obtained as 1:1.47:2.74 for a water to binder ratio = 0.45 and 1:1.27:2.37 for water to binder ratio = 0.4. The water to binder (w/b) ratio values were arrived at 0.4 and 0.45 based on previous literatures of hot weather concrete [19]. To achieve a good workable concrete, the slump between 50 and 75 mm is designed. For M30 grade concrete, trial mixes are designed by partially replacing the cement with aluminium dross at a replacement level of 0%, 10%, 20% and 30%. A total of 8 trial mixes are formulated and designated as M1, M2,. . ., M7 and M8. M1, M2, M3 and M4 belong to the design mix of w/b ratio-0.45; whilst M5, M6, M7 and M8 belong to the design mix of w/b ratio-0.40. The quantities of different materials required for production of 1 m^3 of concrete of M30 grade as per trial mixes are given in Table 2.

2.2. Specimen preparation and exposure

The experimentation was actually carried out during summer at a construction site in the Bellary district of Karnataka state, India. As per Koppen's classification, the Bellary district witnesses a very dry climate with moisture indices less than 10% and therefore it is classified under arid zone [20]. During April and May (peak summer season), the temperature ranging from 33 °C (91 °F) to 46 °C (111 °F) is experienced in the recent 5 years. The various elements of concrete were exposed to the hot sunshine for quite a few hours before commencing the production of concrete. As per IS 10086-1982 [21]; three types of moulds, namely, the standard mild steel cubes of size 150 mm, cylindrical steel moulds measuring 150 mm diameter and 300 mm height and rectangular prism shaped steel moulds of size 100 mm × 100 mm × 500 mm, were used for the moulding of test specimens for determining the compressive strength, tensile strength and flexural strength of the designed concrete respectively. All the moulds were also placed in the hot sun for a couple of hours before commencing the production of concrete. The concrete mixes were prepared outdoors and the mixing was started exactly at noon in an unshaded location. The average temperature at the location was around 42 °C and the mean relative humidity was about 7% on the day of casting of specimens. The prevailing site circumstances fairly represent the hot weather concreting conditions. The details of the total number of specimens tested are provided in Table 3. The concrete was placed into the moulds in three layers of equal thickness and each layer was compacted by using a table vibrator. The concrete specimens were demoulded after 24 hours and immersed in the nearby open water tank for a curing period of 28 days (some specimens were cured up to 90 days). The water temperature at the site was about 35 ± 2 °C during mid sunshine hours and the water temperature during nights gradually reduced to about 28 ± 2 °C, hence we can say that the concrete specimens underwent curing at the diurnal temperature regime.

2.3. Determination of strength and durability properties of aluminium dross concrete

2.3.1. Determination of compressive strength of the concrete

Compressive strength tests are carried out on cubes of size 150 mm as specified by IS: 516–1959 [22]. All the cubes are tested under dry condition, after drying the surface of the specimens containing moisture in them. For each mix proportion (trial mix), three cubes are tested at 7 days, 14 days and 28 days using compression testing machine of 2000 kN capacity at a uniform stress of 149 kg/cm^2/minute, with the specimen properly placed and centred in the testing machine. Some Al dross specimens were cured for 90 days and tested for compressive strength. The ultimate load (P) will be noted down. The compressive strength of the specimen is calculated by using Equation (1)

[1] IS 456–2000 [31] has designated the concrete mixes into a number of grades as M10, M15, M20, M25, M30, M35, M40, M45, M50, M55, M60, M65, M70, M75 and M80. In this designation, the letter 'M' refers to the mix and the numerical value corresponds to the compressive strength of the cube at 28 days of curing expressed as N/mm^2. As per this code, the M10, M15 and M20 grades of concrete are classified as "Ordinary Concrete". The concrete of grades M25 to M55 are classified as "Standard Concrete" and finally the grades above M60 are classified as "High Strength Concrete". In the present study, we have experimented to produce a standard concrete of M30 grade which is neither expensive nor a low strength concrete.

[2] The binder to aggregate ratio of 1:1.47:2.74 refers to proportion of [cement: fine aggregate: coarse aggregate] during weigh batching.

Table 3
Details of specimens tested.

MIX	M1	M2	M3	M4	M5	M6	M7	M8	Total
No. of cubes for determining compressive strength cube size – (L = B = H-150 mm)	9	12	12	12	9	12	12	12	90
No. of cylinders for determining tensile strength cylinder size – (dia-150 mm, height-300 mm)	3	3	3	3	3	3	3	3	24
No. of rectangular prisms for determining flexural strength prism size – (L = 500 mm, B = H = 100 mm)	3	3	3	3	3	3	3	3	24
No of cubes for water absorption test cube size – (L = B = H = 100 mm)	3	3	3	3	3	3	3	3	24
No. of cubes for acid attack test cube size – (L = B = H-150 mm)	4	4	4	4	4	4	4	4	32
Total									194

$$F_c = \frac{P}{A} \quad (1)$$

where: Fc is compressive strength of the concrete specimen in MPa;
P is the ultimate load (load of failure) in Newton;
A is area of cube in mm2.

2.3.2. *Determination of tensile strength of the concrete*

Split tensile strength tests are carried out at the age of 28 days on cylindrical concrete specimens of size 150 mm diameter and 300 mm height conforming to the specifications of IS: 5816-1970 [23]. This test is carried out by using compression testing machine of 2000 kN capacity by placing the cylindrical specimen longitudinally between the loading surfaces of a compression testing machine and the load is applied until the failure of the cylinder, along the vertical diameter. The split tensile strength of the specimens is estimated by using Equation (2)

$$F_t = \left(\frac{2P}{\pi DL}\right) \quad (2)$$

where: F_t is tensile strength of the concrete specimen in MPa;
P is failure load in kN;
D is diameter of the cylinder;
L is length of the cylinder.

2.3.3. *Determination of flexural strength of the concrete*

Flexural strength tests are carried out at the age of 28 days on rectangular prism shaped concrete specimens of size 100 mm × 100 mm × 500 mm using a flexural strength testing machine of 500 kN capacity by subjecting the concrete beam to a two point loading as per the specifications of IS:516–1959 [22]. The flexural strength of the concrete beams are estimated by using Equation (3).

$$F_f = \left(\frac{PL}{BD^2}\right) \quad (3)$$

where: F_f is flexural strength of the concrete specimen in MPa;
P is failure load in kN;
L is length of the cylinder;
B is breadth of the rectangular prism;
D is depth of the rectangular prism.

2.3.4. *Water absorption test on concrete*

The water absorption test is carried out on cubes of size 100 mm at the age of 28 days curing as per the specifications of BS 1881-122 [24]. Initially the specimens are kept for drying in an oven maintained at 105 ± 5 °C for about 72 ± 2 hours. Upon removal of the specimens from the oven, they are kept for cooling in a dry airtight chamber for about 24 ± 0.5 hours. The weight of the dried specimens is measured and noted down. Subsequently, the concrete samples are subjected to complete immersion in a water tank for about 30 ± 0.5 minutes and taken out. Upon removal, all the specimens are wiped out using a dry cloth for making the surface dry and the weight of the concrete sample is evaluated again. The water absorption of the concrete specimens is calculated as the increase in the weight of the specimen from immersion and is usually expressed as a percentage.

$$\text{Water absorption }(\%) = \frac{W_S - W_D}{W_D} \times 100 \quad (4)$$

where: W_S is the weight of the specimen after immersion in water
W_D is the weight of the oven dried specimen

2.3.5. *Acid resistance test on concrete*

The acid resistance experiments are conducted on 150 mm size cube samples after 28 days of curing. The initial weight of the cubes is found and then immersed in water diluted with 5% by weight of sulphuric acid (H_2SO_4) for another 90 days after 28 days of curing. The pH value of the acidic media is maintained at 2. Later, the cubes are picked up from the acid water and the surface of the cubes is wiped off and neatly dressed. Now, the dead weight and the compressive strength of the concrete specimens are measured and the average % loss of weight and compressive strength are studied. The weight and compressive strength of the cubes are found at various ages of 30, 60 and 90 days of exposure in the present case. The loss in weight and compressive strength are calculated as follows,

$$\text{Loss in weight }(\%) = \frac{W_1 - W_2}{W_1} \times 100 \quad (5)$$

$$\text{Loss of compressive strength }(\%) = \frac{\sigma_1 - \sigma_2}{\sigma_1} \times 100 \quad (6)$$

where: W_1 is the weight of concrete cube specimen before immersion in acid.
W_2 is the weight of concrete cube specimen after immersion in acid.
σ_1 is the compressive strength of concrete cube before immersion in acid
σ_2 is the compressive strength of concrete cube after immersion in acid

3. Results and discussion

3.1. Effects of hot weather on plastic properties of Al dross concrete

By visual observation, the fresh aluminium dross concrete mixes were homogeneous, cohesive, thick, viscous and sticky due to the high volume of fines and optimum water content suitable for hot weather conditions. Once the aluminium dross concrete has been placed into the forms and is still in a plastic state, the high site temperature at the surface of the concrete can cause problems associated with setting time of concrete, rate of slump loss, curing and plastic shrinkage cracking. The properties of fresh aluminium dross concrete are studied in terms of slump and compaction factor tests. The concrete produced with aluminium dross showed a marginal sensitivity to temperature than the normal concrete. The concrete without any admixture had a nearly linear response to site temperature. Slump of Al dross concrete decreased approximately by 8 mm for 30% replacement of cement by Al dross which is quite negligible. The workability properties of different trial mixes have been measured and tabulated in Table 4. From the test results, it can be observed that the workability of concrete mixes decreases as the percentage of aluminium dross content in concrete increases (Fig. 2). With the incorporation of aluminium dross as a retarding admixture in concrete, there was a considerable reduction in the workability for the same water to binder (w/b) ratio as that of concrete mix without admixture. This is because the water available in the system for maintaining workability decreases due to absorption of water over the high specific surface area of aluminium dross, thereby decreasing the consistency as well. Hot weather increases the hydration of cement, resulting in a faster setting of concrete, which denotes the reduced availability of time for placing and finishing of concrete. With the use of aluminium dross, a delay in the setting of concrete is observed. The mortar produced with

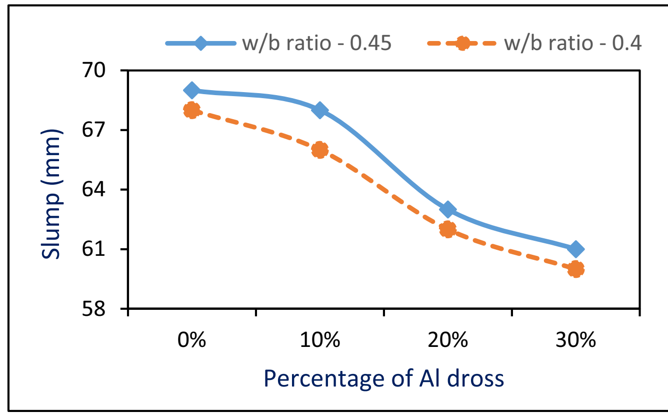


Fig. 2. Workability of aluminium dross concrete evaluated in terms of slump value.

20% aluminium dross blending rendered a 30 minute delay in the initial setting time, realized using penetrometer test as per IS:8142-1976 (1976) [25]. However, the final setting time of 20% aluminium dross concrete was attained after 720 minutes (12 hours). The alkali-silica reaction was not observed in the test specimens due to a lesser percentage of silica content in the Al dross.

3.2. Compressive strength of Al dross concrete

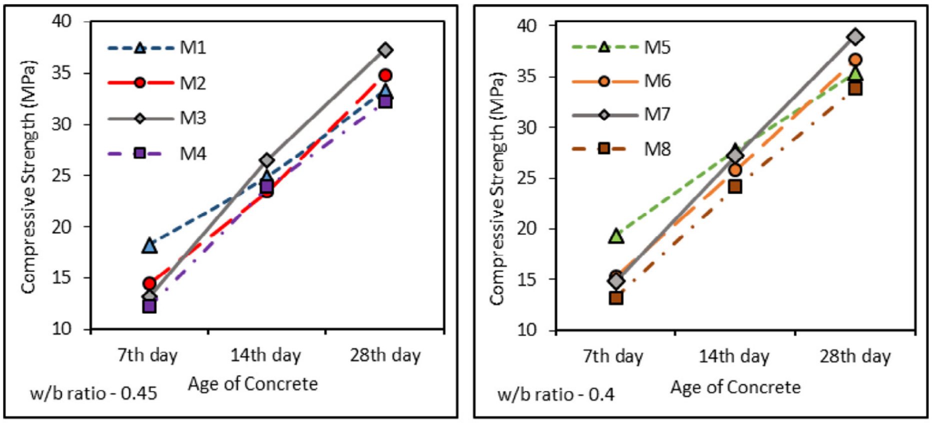
The cube compressive strength results at ages such as 7, 14 and 28 days of the aluminium dross concrete (mixes having binder replacement levels such as 0%, 10%, 20%, and 30%) having different water to binder ratios such as 0.4 and 0.45 are presented in Table 5 and are plotted in Fig. 3(a) and (b). From the test results it is observed that the maximum compressive strength is obtained for the mix with 20% aluminium dross at 28 days age for both the water to binder ratios. The concrete of w/b ratio = 0.40 is found to be superior to the concrete of w/b ratio = 0.45 at the age of 28 days. The early strength of concrete, i.e., at the age of 7 days, the concrete with 0% admixture (Al dross), is found to gain the maximum compressive strength. The compressive strength development in aluminium dross concrete is influenced by the refinement of microstructure, transformation of CH into CSH gel through the pozzolanic reaction and formation of a denser interfacial transition zone. From Fig. 3(a) and (b),

Table 4
Workability properties of aluminium dross concrete.

Mix designation	Properties			
	Slump (mm)	Standard deviation	Compaction factor	Standard deviation
M1	69	±2.3	0.9	±0.03
M2	68	±2.25	0.88	±0.02
M3	63	±2.25	0.86	±0.02
M4	61	±2.4	0.86	±0.03
M5	68	±2.3	0.89	±0.02
M6	66	±2.4	0.87	±0.03
M7	62	±2.25	0.85	±0.03
M8	60	±2.3	0.84	±0.03

Table 5
Cube compressive strength results of aluminium dross concrete.

Mix designation	7th day compressive strength (MPa)	Std. dev (σ)	14th day compressive strength (MPa)	Std. dev (σ)	28th day compressive strength (MPa)	Std. dev (σ)
M1	18.2	0.23	24.85	0.36	33.3	0.57
M2	14.45	0.41	23.4	0.48	34.8	0.45
M3	13.15	0.35	26.5	0.52	37.25	0.48
M4	12.2	0.52	23.9	0.44	32.2	0.51
M5	19.35	0.39	27.75	0.38	35.35	0.53
M6	15.3	0.47	25.8	0.49	36.65	0.49
M7	14.85	0.49	27.2	0.47	38.95	0.56
M8	13.25	0.28	24.15	0.51	33.85	0.55



(a) w/b ratio – 0.45 (b) w/b ratio – 0.40

Fig. 3. Cube compressive strength results of aluminium dross concrete.

it can be observed that the cubes made of aluminium dross attain 40 to 50% of designed compressive strength at the age of 7 days and 80 to 90% of the design strength is obtained at the age of 14 days itself. With the replacement of 30% of cement by Al dross, the compressive strength of the concrete decreased because the C-S-H gel formation is hindered due to unavailability of sufficient SiO_2 content in the concrete mix. The C-S-H gel formation is primarily dependent on the reaction of CaO and SiO_2 in water and is one of the major compounds responsible for the strength in concrete.

Upon testing the 90th day compressive strength of a concrete cube specimen of w/b ratio–0.4, produced by 20% replacement of cement with aluminium dross, the strength gain curve is plotted as shown in Fig. 4 and it may be seen that the early age strength gains are much more rapid than at later ages. The proper curing of concrete benefits the strength development at early ages. In the present research it is observed that the concrete can lose 67% of its strength if not cured properly when it is exposed in hot weather with a low humidity.

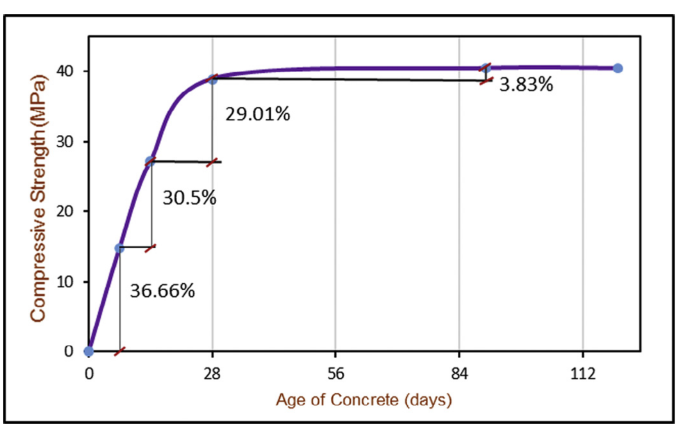


Fig. 4. Strength gain curve for aluminium dross concrete.

3.3. *Tensile strength of Al dross concrete*

The split tensile strength results of aluminium dross concrete mixes of different water to binder ratios such as 0.40 and 0.45 at the replacement levels such as 0%, 10%, 20% and 30% of aluminium dross at the age of 28 days are presented in Table 6. The variations of splitting tensile strength at 28 days with different percentage of aluminium dross are shown in Fig. 5. From the experimental results, it can be observed that the maximum splitting tensile strength is obtained for a mix with 20% replacement of cement by aluminium dross at water-binder ratio of 0.4. We can also witness that the splitting tensile strength increases with the increase in Al dross content up to 20%; beyond this, the tensile strength decreases gradually. The increase in the tensile strength of the concrete produced by replacing 20.0% aluminium dross is because of the distinct densification of the concrete. Aluminium dross, due to its high surface area and chemical composition, enhances the tensile strength property of Al dross concrete by reducing the binder paste-aggregate transition zone. At 20% replacement of the aluminium dross content, the area fraction of porosity in the cement paste decreases due to the fineness of aluminium dross particles, and the density of cement paste increases leading to enhancement of tensile strength of concrete.

3.4. *Flexural strength of Al dross concrete*

The results of flexural strength of aluminium dross concrete mixes for different water-binder ratios such as 0.40 and 0.45 at the age of 28 days are presented in Table 7. The variations in

Table 6
Split tensile strength results of aluminium dross concrete at the age of 28 days.

Mix designation	M1	M2	M3	M4	M5	M6	M7	M8
28th day tensile strength (MPa)	4.2	4.3	4.75	3.8	4.4	4.6	4.95	4.05
Std. dev (σ)	0.28	0.32	0.27	0.35	0.33	0.29	0.39	0.37

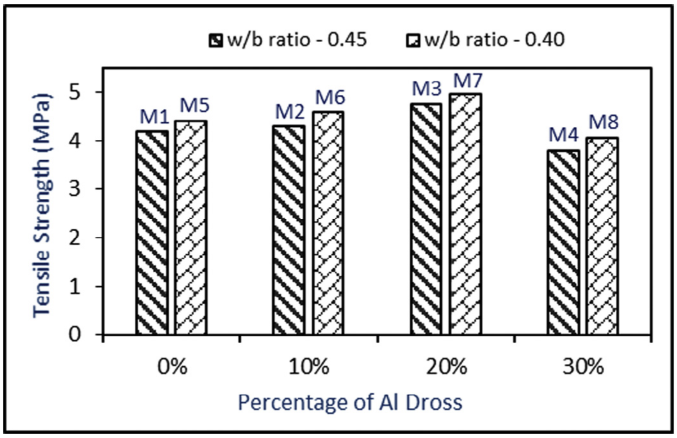


Fig. 5. Split tensile strength of aluminium dross concrete at the age of 28 days.

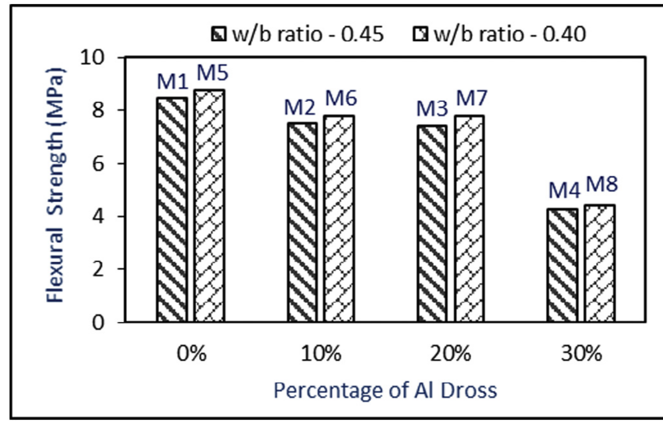


Fig. 6. Flexural strength of aluminium dross concrete at the age of 28 days.

flexural strength at the age of 28 days with different percentage of aluminium dross are plotted in Fig. 6. From the experimental results, it is observed that the maximum flexural strength is obtained for concrete mixes without aluminium dross. In the present study, it is observed that the flexural strength of Al dross concrete is reasonably safe up to 20% replacement of Al dross. At 30% replacement level of Al dross, the "excess" fine particles tend to adhere to the surface of coarse aggregates and prevent proper bonding between the cement paste and the aggregate. This results in the formation of a weak aggregate-paste bond that promotes intensive segregation and weakens the concrete. Another reason for the decrease of strength is due to the modification of orientation index of the aggregates in the concrete matrix which causes inhomogeneity in the distribution of hydration products at hot weather conditions.

3.5. Water absorption of concrete

The most essential factor governing concrete durability is the penetration of water, gas and ions which depends on the micro structure and porosity. Hence in this study, experimental investigation is carried out on the test specimen to ascertain the durability related property such as water absorption and acid resistance of the aluminium dross concrete.

The movement of various fluids through concrete takes place not only by flow through the porous system but also by diffusion and absorption. The water absorption test results are presented in Table 8 and its graphical representation is shown in Fig. 7. From the results it can be seen that the concrete with 30% aluminium dross blending is less vulnerable to absorption. The concrete cubes of w/b ratio-0.4 are found to have reduced water absorption than the concrete of w/b ratio-0.45. The possible reason for this behaviour is that the higher w/b ratio mix contains excess water in it which occupies the space in concrete and as it evaporates, it leaves more voids, thus increasing the water absorption value. Since the concrete was placed under hot weather conditions, there might be an accelerated rate of hydration of cement and the water in the concrete mix could have been dried out rapidly, making the concrete more porous.

3.6. Acid resistance of Al dross concrete

Acids attack concrete by dissolving both hydrated and unhydrated cement compounds as well as calcareous aggregate. In most instances, water-soluble calcium compounds are formed due to the chemical reaction between acidic solution and specimen, which are then leached away. Siliceous aggregates are resistant to most acids and other chemicals and are sometimes specified to improve the chemical resistance of concrete [26]. In the present study, the effect of sulphuric acid is analysed on aluminium dross concrete. The concrete mixes tested for finding loss in weight and loss in compressive strength are presented in Table 9 and Table 10 respectively. At the end of each period of 30, 60 and 90 days, the concrete specimens were removed from the chemical solutions, cleaned with water and weighed. Consequently the specimens were tested for compressive strength.

By visual observations it is seen that the surface of Al dross concrete cubes is less affected from that of control concrete. The control concrete (0% Al dross content) permitted surface deterioration of 2 mm on all the faces after 30 days of acid bath. Due to the high packing density and fine microstructure of Al dross concrete, the penetration of acid solution is less when compared to that of control concrete. The deposition of powder over the surface of the concrete blocks is seen at about 60 days of acid bath. Finally, after 90 days, a change in the colour of the specimens from grey to white is seen due to intense surface deterioration. The percentage weight loss of Al dross concrete

Table 7
Flexural strength results of aluminium dross concrete at the age of 28 days.

Mix designation	M1	M2	M3	M4	M5	M6	M7	M8
28th day flexural strength (MPa)	8.45	7.5	7.4	4.25	8.75	7.8	7.8	4.4
Std. dev (σ)	0.45	0.53	0.55	0.49	0.58	0.53	0.49	0.52

Table 8
Results of water absorption test on Al dross concrete.

Mix designation	Wet weight of the specimen (kg)	Dry weight of the specimen (kg)	Water absorption (%)
M1	8.4	7.9	6.33
M2	8.8	8.4	4.76
M3	8.7	8.4	3.57
M4	8.9	8.6	3.48
M5	8.4	8.0	5.0
M6	8.7	8.4	3.57
M7	8.7	8.5	2.35
M8	8.8	8.6	2.32

Table 10
Loss in compressive strength (C.S) of concrete mixes due to acid attack (5% H_2SO_4).

Mix Designation	% loss in C.S @ 30 days	% loss in C.S @ 60 days	% loss in C.S @ 90 days
M1	5.11	13.98	19.25
M2	2.73	7.05	10.22
M3	2.15	7.26	10.75
M4	2.64	7.78	11.51
M5	4.95	12.45	20.23
M6	1.78	7.11	10.12
M7	2.06	7.33	10.80
M8	3.25	7.99	11.39

mixes of M30 grade after immersing in 5% H_2SO_4 solution increases corresponding to the time of exposure. However the weight loss of concrete with 0% Al dross is much higher at all periods when compared to that of blended concrete mixes (Fig. 8). The percentage weight loss of 10% Al dross mixes are less when compared to the other two mixes (20% and 30% replacement mixes) (Fig. 9). The reason may be due to higher dissolution of both hydrated and unhydrated cement compounds in the other two mixes. In alumino pozzolans like Al dross, the alumina content of dross participates in reactions with calcium hydroxide producing various calcium-aluminate hydrates (C-A-H) and calcium-alumino-silicate hydrates (C-A-S-H) [27]. At 10% replacement of Al dross, there will be a dense interlocking network of crystalline calcium alumino-silicate hydrates which leads to lesser permeability of concrete.

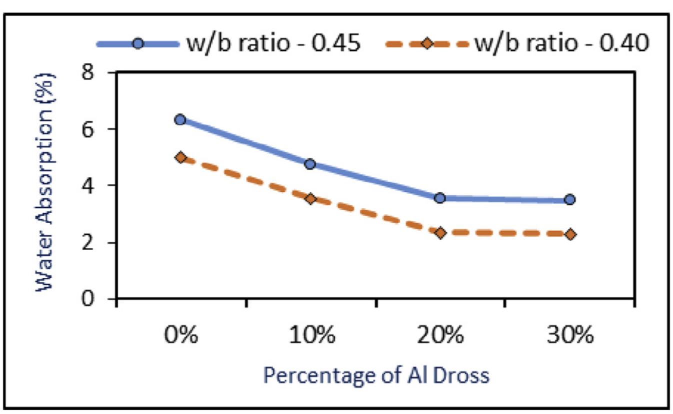


Fig. 7. Water absorption results of Al dross concrete at the age of 28 days.

On the other hand, at 30% replacement, the sulphuric acid attacks the concrete by reacting with abundant calcium hydroxide $Ca(OH)_2$ and calcium silicate hydrate (C-S-H) gel and forms gypsum like substrate, thereby causing the breakdown of the cement hydrate structure. From Table 9 it can be noted that the weight loss of the concrete specimens increased when the water to binder ratio decreased from 0.45 to 0.40. Al-Amoudi et al. [28] and Al-Amoudi [29] observed the same effect in their studies related to cement exposed to sulphate environments. The dense microstructure of the specimens (of low w/b ratio) and their limited pore space for the deposition of products of expansive reaction are liable for the inferior performance of low w/b ratio. The specimens of low w/b ratio fail to accommodate the salt crystallization in the very fine pore structure and thereby produce higher expansion and deterioration than the specimens prepared with a high w/c ratio.

Table 10 displays the percentage compressive strength loss of Al dross concrete mixes of M30 grade after immersing in 5% H_2SO_4 solution. The percentage compressive strength loss of Al dross concrete mixes increases corresponding to the time of exposure. For Al dross blended concrete mixes, the percentage compressive strength loss is relatively less when compared to that of concrete with 0% Al dross (Fig. 10). This may be attributed to the reduced permeability and better pore space refinement in Al dross concrete.

3.7. XRD analysis of aluminium dross concrete

X-ray diffraction is a direct method for finding crystalline phases present in the concrete [30]. The X-ray diffraction patterns were determined for the concrete samples, i.e. 20%

Table 9
Loss in weight of concrete mixes due to acid attack (5% H_2SO_4).

Mix designation	Wt. before immersion @ 30 days (kg)	Wt. after immersion @ 30 days (kg)	% loss in wt. @ 30 days	Wt. after immersion @ 60 days (kg)	% loss in wt. @ 60 days	Wt. after immersion @ 90 days (kg)	% loss in Wt. @ 90 days
M1	7.95	7.79	2.01	7.58	4.65	7.35	7.53
M2	8.45	8.36	1.06	8.25	2.36	8.05	4.73
M3	8.5	8.39	1.29	8.26	2.82	8.08	4.94
M4	8.6	8.47	1.51	8.32	3.26	8.15	5.23
M5	8.05	7.87	2.23	7.66	4.84	7.43	7.70
M6	8.35	8.25	1.19	8.13	2.63	7.93	5.02
M7	8.5	8.38	1.41	8.24	3.06	8.05	5.29
M8	8.65	8.51	1.62	8.35	3.46	8.14	5.89

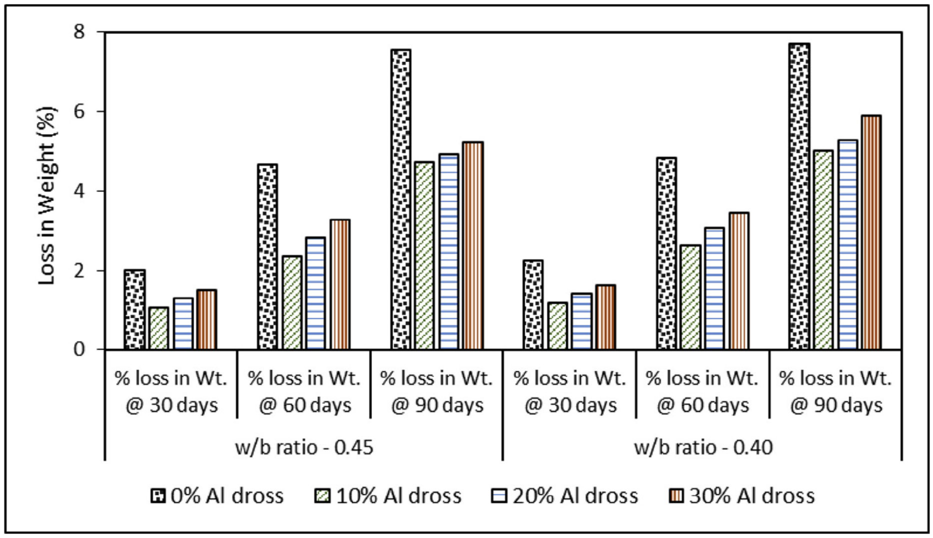


Fig. 8. Plot of loss in weight of concrete mixes due to acid attack (5% H_2SO_4).

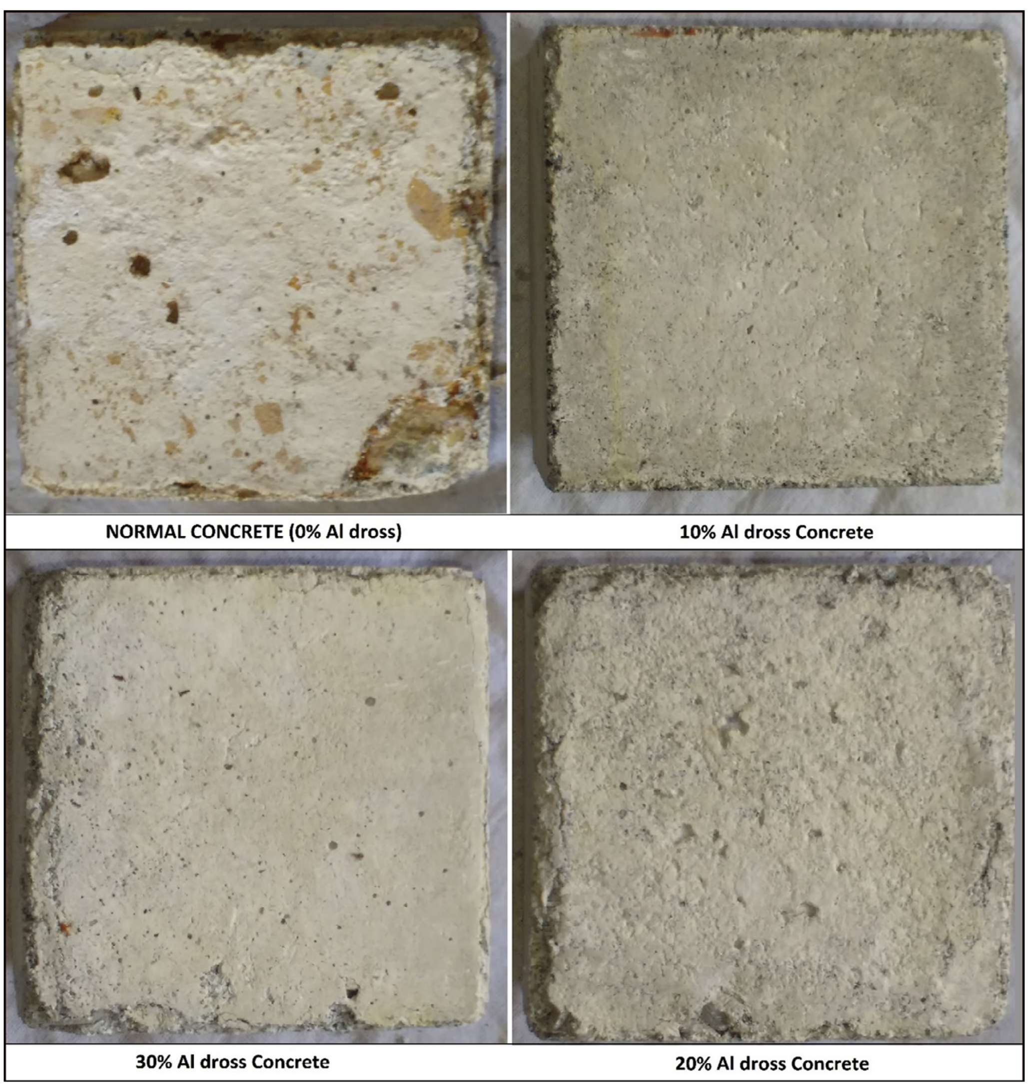


Fig. 9. Concrete cube specimens after 30 days of acid test (the specimens belong to the mixes produced with w/b ratio-0.4).

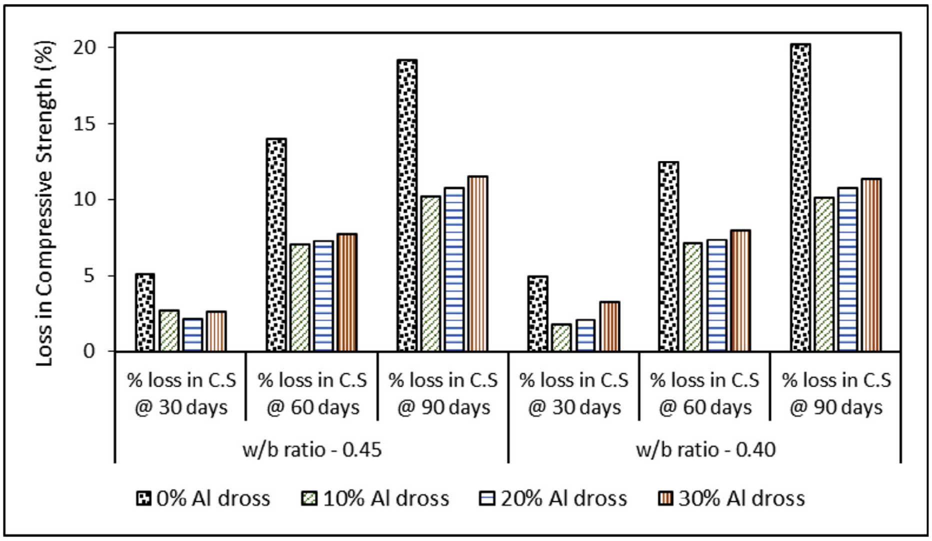


Fig. 10. Plot of loss in compressive strength of concrete mixes due to acid attack (5% H_2SO_4).

aluminium dross mix and 0% Al dross mix of 0.4 w/b ratio which were sufficiently cured. The X-ray diffraction pattern of samples with 20% Al dross and 0% Al dross is shown in Figs 11 and 12 respectively. From Fig. 11 it is seen that quartz (SiO_2) content is the major component present in the 20% Al dross concrete sample detected as a peak on 2θ angle of 26.75°. The additional crystalline compounds identified include corundum (Al_2O_3) present at 20°, 29.5° and 68°; calcium silicate (Ca_3SiO_5) present at 21° and 39.5°; mullite Al ($Al_{1.3}Si_{0.52}O_{3.8}$) present at 37° and 50°; portlandite ($Ca(OH)_2$) present at 62°; microcline ($KAlSi_3O_8$) present at 60.25°; and albite ($NaAlSi_3O_8$) present at 35°. The XRD analysis of 0% Al dross concrete sample (Fig. 12) shows major peaks of quartz (SiO_2) and calcium silicate (Ca_3SiO_5). Quartz (SiO_2) is observed at a predominant peak of 29.5° while calcium silicate (Ca_3SiO_5) is observed at 26.5°. Other compounds such as portlandite ($Ca(OH)_2$), microcline ($KAlSi_3O_8$), albite ($NaAlSi_3O_8$) and silicon carbide (SiC) are also spotted in the XRD pattern of 0% Al dross concrete. The results infer that the intensity peaks of calcium silicate (Ca_3SiO_5) and portlandite $Ca(OH)_2$ in the XRD patterns of 20% Al dross concrete decreased when Al dross is substituted with cement. The finer aluminium dross had a more glossy matter resulting in a higher utilisation of portlandite $Ca(OH)_2$. The decrease in portlandite can be attributed to the carbonation and pozzolanic reactions in the 20% Al dross concrete.

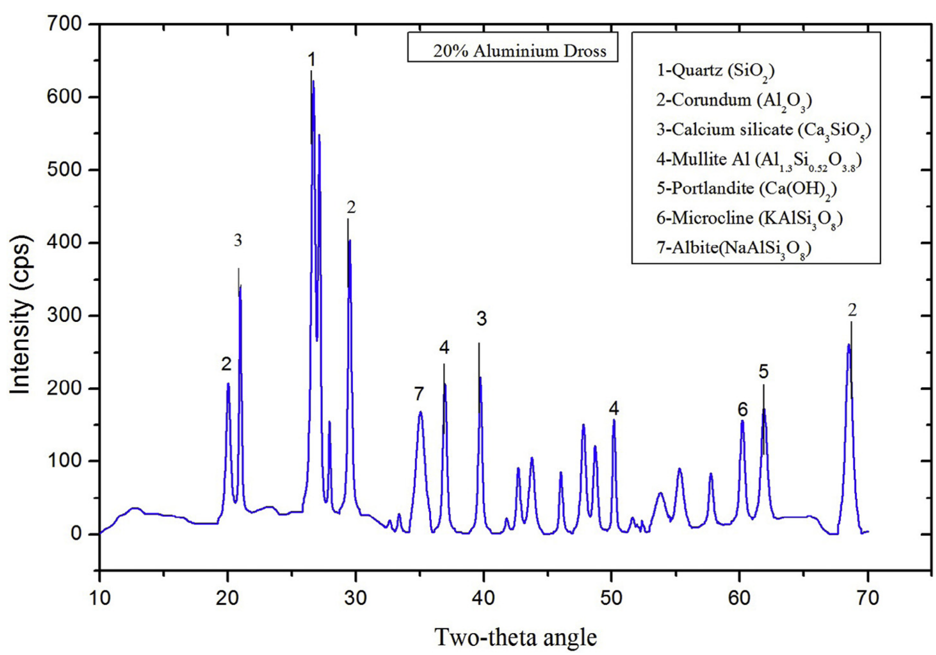


Fig. 11. X-ray diffraction pattern of 20% aluminium dross concrete sample.

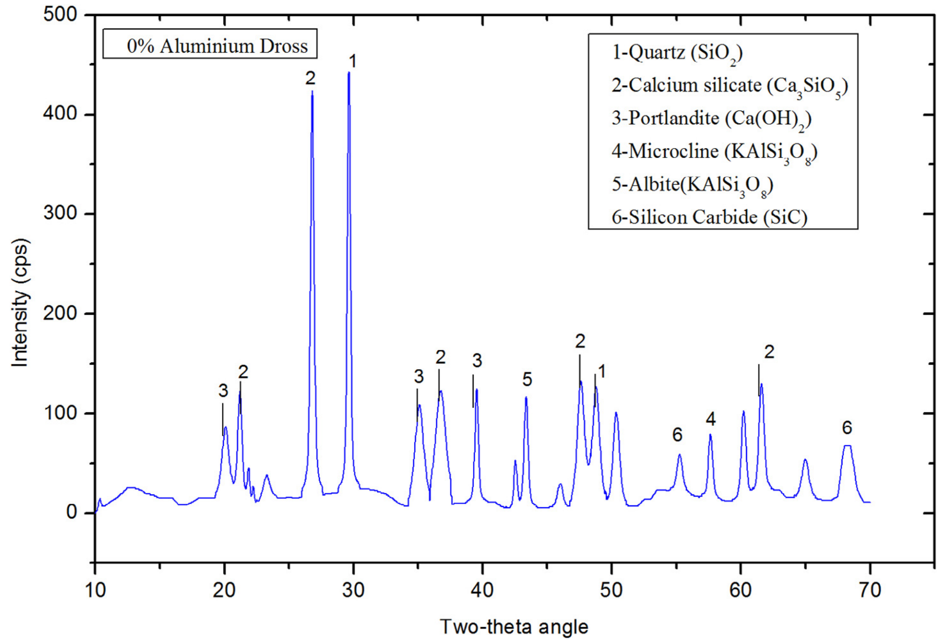


Fig. 12. X-ray diffraction pattern of 0% aluminium dross concrete sample.

4. Conclusions

Focusing towards research on aluminium dross as a pozzolana, many researchers either studied the performance of Al dross concrete under normal laboratory concreting conditions or investigated the properties of Al dross in order to produce high alumina cement. The current research work carried out focused towards exploring the role of Al dross concrete for hot weather concreting. The following conclusions are drawn from the various experimental results reported in the present work.

- The concrete produced with 20% aluminium dross replacement gave optimum strength and decent workability for hot weather concreting situation. With the incorporation of aluminium dross as a retarding admixture in concrete there was a slight reduction in the workability due to absorption of water over the high specific surface area of aluminium dross.
- The w/b ratio-0.4 is found to be better than w/b ratio-0.45 from the strength aspects. Upon exposure to acidic environment, the Al dross blended concrete, principally those produced with w/b ratio- 0.4, exhibited marginally lesser performance in terms of compressive strength reduction and weight loss of concrete. The specimens of low w/b ratio fail to accommodate the salt crystallization in the very fine pore structure and thereby produce higher expansion and deterioration than the specimens prepared with a high w/c ratio.
- The mortar produced with 20% aluminium dross blending rendered a 30 minute delay in the initial setting time, realized using penetrometer test. However, the final setting time of 20% aluminium dross concrete was attained after 720 minutes.
- The concrete produced with 30% Al dross replacement experiences a higher rate of flexural strength reduction due to inhomogeneity in the distribution of hydration products in concrete at hot weather conditions.
- The Al dross improves the durability of concrete. The water absorption of Al dross concrete is significantly less as compared to that of control concrete.
- The Al dross concrete showed about 20–30% more resistance to acid attack. The exposure of Al dross concrete to the acidic solution of pH = 2 resulted in the decrease of compressive strength up to 12% and reduction in weight of about 5%. The weight and strength loss of control concrete (0% Al dross content) are much higher at all periods when compared to that of Al dross blended concrete mixes.
- The percentage of calcium silicate (Ca_3SiO_5) and portlandite $Ca(OH)_2$ decreased with the substitution of cement with 20% aluminium dross.
- The 20% aluminium dross blend concrete exhibited new compounds such as corundum (Al_2O_3), mullite Al ($Al_{1.3}Si_{0.52}O_{3.8}$), additional to quartz (SiO_2), calcium silicate (Ca_3SiO_5) and portlandite $Ca(OH)_2$.
- The option of substituting cement with industrial by-product such as aluminium dross tenders economic, technical and ecological benefits which are of great significance in the present-day agenda of sustainability in the construction sector.

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