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Research article

Hybridization of concrete by the inclusions of kaolin, alumina and silica fume: Performance evaluation

Anandh Babu Malayali [a], Venkatesh R [b,*], Sulaiman Ali Alharbi [c], M.A. Kalam [d]

[a] Department of Civil Engineering, Sethu Institute of Technology, Kariapatti, Virudhunagar, 626115, Tamilnadu, India
[b] Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Chennai, 602105, Tamilnadu, India
[c] Department of Botany and Microbiology, College of Science, King Saud University, PO Box - 2455, Riyadh, 11451, Saudi Arabia
[d] School of Civil and Environmental Engineering, FEIT, University of Technology Sydney, NSW, 2007, Australia

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ABSTRACT

Concrete is the prime source, which fulfils the applications for construction in various forms. The prime roles of concrete industries are reducing material usage, enrichment of compressive strength, and flexural strength of concrete usage. This research focuses on recycling kaolin (mining waste) and silica fume, a great potential material for replacing coarse aggregate gravel stone and fine aggregate sand in conventional concrete as a hybrid. The developed concrete contained 5% nano alumina (Al_2O_3), 10% of kaolin waste (KW), and 5, 10, and 15% of silica fume (SF), and its behavior like compressive strength, flexural strength, water absorption, and acid attack behavior is studied. The molecular structure of crystalline is analyzed via X-ray diffraction (XRD). The 15% SF blended with 5% alumina and 10% KW cured within 28 and 90 days recorded high compressive and flexural strength (44 ± 1.76 MPa and 4.3 ± 0.17 MPa). XRD pattern proved their alumina, SF, and KW and found that the concrete blended with 5% alumina, 10% KW, and 15 wt% SF(90 days cured concrete) showed low water absorption (3.1 ± 0.12%). The effect of sulfuric acid behavior on weight reduction was 0.78% compared to CC1 (concrete cube without Al_2O_3, SF, and KW).

1. Introduction

For more than 100 years, the revolutions of concrete have gained significant positions globally for construction applications [1]. Conventional concrete was developed with ordinary Portland cement, fine aggregate sand, and coarse aggregate gravel (less than 20 mm) blended with water [2]. It showed the low compressive strength and crack propagation initiated during live load [3]. To overcome the drawbacks, researchers were forced to locate the problem statement and identify an alternative instead of the conventional sand material [4,5]. Moreover, mine waste rocks [6], mineralogical substitution [7], graphite particle nanostructures [8], burning of quinary [9], fly ash/nanomaterial combinations [10,11], doped/colloid flake carbon [12], graphite nanoparticles [13,14], wheat straw [15], miller/maize [16], natural pozzolan [17], silica fume [18,19], wheat straw ash particles [20], fly ash-slag combinations [21], oil shale ash [22], coir fiber [23], Jute/bamboo fiber [24], natural fiber [25], sugarcane waste bagasse ash [26], nano silica [27], and industrial, agricultural, and demolition waste materials [28] was used as partial alternatives for fine aggregate instead

* Corresponding author.
E-mail address: venkidsec@gmail.com (V. R).

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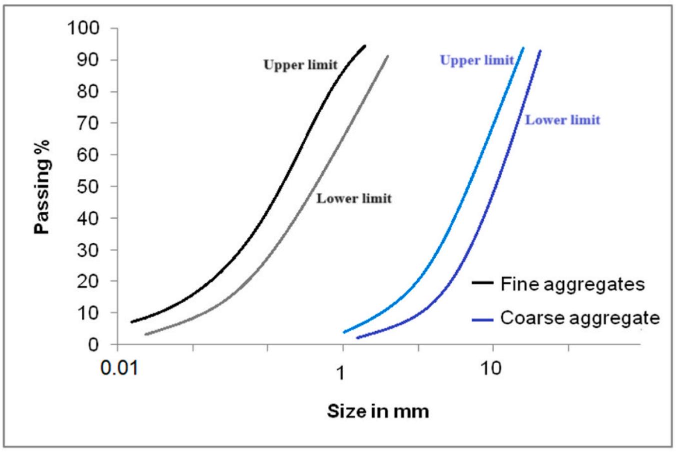
of sand materials. In addition, the concrete characteristics were enhanced by adding natural chopped fiber [29].

Kirgiz et al. [30] developed marble/brick powder concrete and studied its strength mechanism. The green mortar with marble/-brick powder exposed better structural behavior and high compressive strength. Similarly, the concrete is made with different marble and brick power percentages. Impacts of marble/brick power on concrete's compressive/flexural strength are evaluated by 7, 14, 28, and 90 days of curing, and its results revealed better compressive and flexural strength [31,32]. The quality and durability of silica fume and aluminium silicate developed mortar was evaluated, and it was reported that the aluminium silicate offered good chemical resistance and facilitated good compressive and flexural strength [33]. High-strength refractory concrete was synthesized with calcium alumina cement blended with waste instead of aggregate, and 16 samples were developed for structural evaluation. They reported that the concrete contained 50% silica, and 50% aggregate showed the maximum flexural and compressive strength [34].

Chand et al. [35] prepared concrete with Portland cement, silica fume, metakaolin, and glass powder, cured it for 28 days, and found 13.42% improved compressive strength. The microscopic results showed that their calcium silicate hydrate was identified as dense. Zhao et al. [36] studied the effect of binder ratio on the behavior of seawater cement paste blended with silica fume and metakaolin. They found linear interactions between binding ratios of chloride to macropores volume. The thermodynamic formulation of Portland cement with alumina mortar was analyzed, and it was reported that the reactive alumina facilitated 5.75% of the Portland cement mix [37]. However, the silica fume and metakaolin in concrete were found to have superior compressive strength with minimized capillary action (low porosity) [38]. Additionally, alumina was good resistance against the sulphate reaction [39]. Recently, aluminium production waste utilized concrete was found to be sustainable compared to conventional developed concrete [40]. With the contribution of metakaolin-based concrete, it has better durability [41,42] and exposed self-compacting behavior [43]. Recently, waste foundry sand-made concrete mixture exposed superior mechanical/durability behavior [44,45].

Recent literature shows that silica fumes lead to good adhesive behavior, and alumina could resist chemical reactions compared to all others. In addition, they provide good sustainability with minimized capillary action. For this reason, the present investigation is to select the concrete mixture by the inclusions of ordinary Portland cement, fine sand, coarse aggregate gravel, 5% nano alumina (Al_2O_3), 10% of kaolin waste (KW), and 5, 10, and 15% of silica fume (SF), and require the amount of water. Therefore, the current work is to enhance the compressive/flexural strength and limit the water absorption behavior of concrete by using 5% nano alumina (Al_2O_3), 10% of kaolin waste (KW), and 5, 10, and 15% of silica fume (SF).

a) Alumina nanoparticles, b) Kaolin waste, and c) Silica fume



(d) illustrates the fine and coarse aggregate gradation.

Fig. 1. Secondary materials: a) Alumina nanoparticles, b) Kaolin waste, and c) Silica fume
Fig. 1(d) illustrates the fine and coarse aggregate gradation.

2. Materials and methods

2.1. Materials

The M20 concrete grade was preferred (1:1.5:3). This mixture contained ordinary Portland cement (OPC 32.5), fine aggregate sand, and coarse aggregate gravel stone (one cubic meter of gravel size is less than 20 mm), with the required quantity of water as the prime material [1,28]. The alumina (50 μm) was chosen as a secondary additive. The kaolin waste (less than 75 μm) and silica fume (50 μm) were chosen as reinforcements as the partial replacement instead of coarse aggregate gravel stone and fine aggregate sand material is shown in Fig. 1(a–c) and (d) illustrates the fine and coarse aggregate gradation. The physical and chemical properties of present materials used for concrete fabrication are exposed in Table 1.

The detailed mixing proportion for cubic meters is shown in Table 2. Among the various materials, Silica fume and kaolin (mining waste) offered good adhesive behavior with superior compressive strength with minimized capillary pores (low porosity) [35,38]. The alumina was chosen as the reason for good resistance against the sulphate reaction [39]. Moreover, the sieve analysis is followed by the ASTM C136M standard for coarse and fine aggregate performance.

2.2. Concrete preparation

Fig. 2 illustrates the flow process diagram for preparing conventional M20 (1:1.5:3) concrete with and without alumina, SF, and KW materials.

Initially, Portland cement, fine sand, coarse aggregate gravel stone, water, alumina, kaolin waste, and silica fume were weighted individually per the mixing ratio (Table 2) via a digital balancing machine.

After weighing, the materials were mixed with water via a mechanical mixer machine at 50 rpm for 3 min. The mixed concrete slurry was poured into the steel cube (0.15 m × 0.15 m X 0.15 m) and compacted via a vibrator tool. The concrete mould was evenly laid up with a flat surface. After one day, the moulded concrete cubic structures were subjected to a curing process under contaminants-free water. Initially, 24–48h and the curing process was extended for 28 and 90 days, respectively [27,28]. It helps increase the strength of the composite [12]. During curing, it is protected from harsh weather conditions like higher temperatures and is open to sunlight, rain, and wind, which may impact hydration. Similarly, the concrete was prepared for further investigation (varied dimensions). Finally, the cured concrete cubic blocks were subjected to XRD, and compressive and flexural strength, water absorption, and low acid attack behavior were studied.

2.3. Characteristics study

2.3.1. X-ray diffraction analysis

Rigaku International made a smart lab X-ray diffractometer (XRD), which was used to identify the phase composition of the developed concrete cubic block, followed by the ASTM C1365 standard [28]. Among the various analyses for surface phase analysis, the XRD is efficient in monitoring the variations between the atomic plane [1].

2.3.2. Compressive and flexural strength

The compressive and flexural strength of the developed concrete cube with and without filler material was evaluated by Instron universal testing machine (UT40 model), and FIE (Fuel Instruments & Engineers) made flexural strength testing TM-74D model used for measure the flexural strength of concrete cubic block under ambient temperature. It was followed by ASTM C109 and ASTM C78 standards [27,28].

2.3.3. Water absorption

The ASTM C1585 standard [33] estimated the water absorption quality of the developed concrete cubic block. Each week of 28 and 90 days evaluated capillary action during the water absorption.

2.3.4. The behavior of an acid test

The durability of the developed concrete sample with high compressive and flexural strength was subjected to an acid behavior test. Before the test, it was weighted as W1 and immersed in a Sulfuric Acid solution with 0.2 N morality for 28 days. After the process, it was weighted again as W2. The relations of W1 and W2 calculated the weight reduction [29].

Table 1
Physical and chemical properties of materials used in present concrete.

Physical and chemical properties	Portland cement	Sand	Stone crush	water	Alumina	Silica fume	Kaolin waste
Density in kg/m^3	1440	1650	1600	997	3960	1500	430
Specific gravity	3.05	2.65	2.59	1	3.55	2.3	2.6
pH	12.5–13	7	>6	6–8.5	6	3	4
Weight of SiO_2 in %	21.18	92	72.04	–	–	93.38	57.5

Table 2
Concrete mixing proportions for cubic meter.

Concrete mixing design (Test Concrete cube)	Mixing density of concrete in kg/m^3						
	Ordinary Portland cement	Sand	Stone crush	water	Alumina	Silica fume	Kaolin waste
	PC	S	SC	W	Al_2O_3	SF	KW
CC1	400.00	600.00	1200.00	200.00	0.00	0.00	0.00
CC2	400.00	600.00	1080.00	200.00	120.59	0.00	120.00
CC3	400.00	570.00	1080.00	200.00	120.59	30.00	120.00
CC4	400.00	540.00	1080.00	200.00	120.59	60.00	120.00
CC5	400.00	510.00	1080.00	200.00	120.59	90.00	120.00

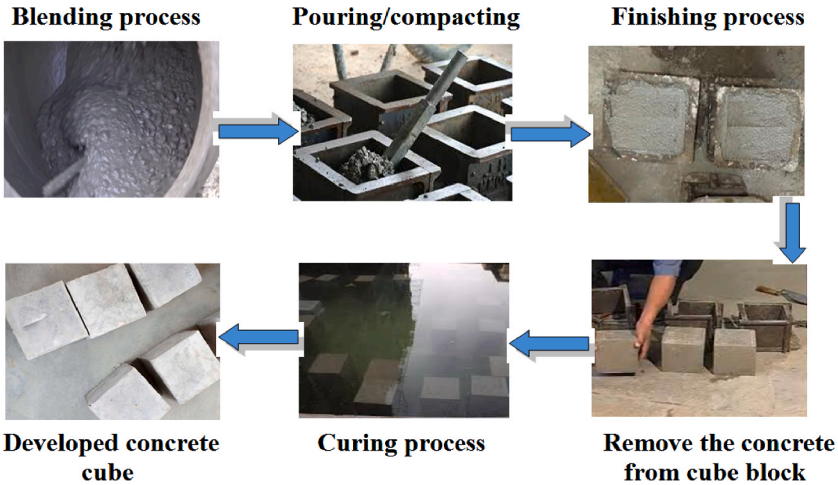


Fig. 2. Actual flow process illustration for concrete preparation.

3. Results and discussion

3.1. XRD analysis of developed concretes

The XRD peaks for conventional M20 grade concrete developed with and with alumina and KWare shown in Fig. 3.

The prime binding Portland cement phase with hydrated cement paste is spotted in the peak of 2theta = 36°, and 2theta = 39° broad peak is identified. This 2theta = 36° noted by (200). The homogenous blending actions result in even peaks for all the concrete structures [6]. The strong, sharp peaks of (111) were identified 2theta = 43°, indicating gravel stone (Quartz). It is the major peak, occupying 1/3rd of the concrete portion [29]. The alternative peaks depend on the concrete structure's mixing compositions and

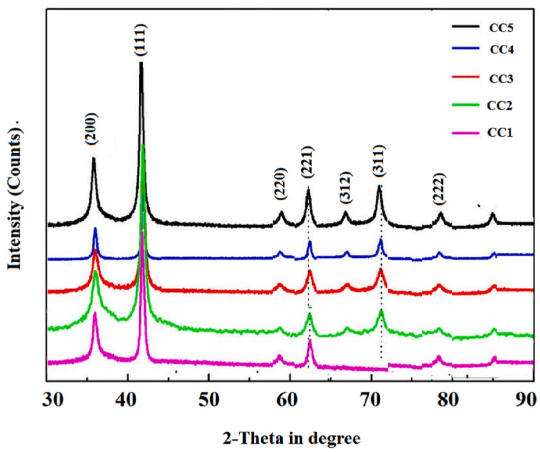


Fig. 3. XRD peaks for developed concretes (CC1, CC2, CC3, CC4, and CC5).

cement paste. The variations in XRD peaks of CC2 showed the alumina (312) and KW (311) as 5 and 10%, respectively. It was recorded by 2theta = 65° to 75°. The sand, along with cement paste, was confirmed by the peaks of (220), (221), and (222), respectively. Moreover, the appearances of Al_2O_3 and KW in the concrete CC3, CC4, and CC5 proved their presence along with fine sand with uniform peaks. The uniform peaks result in increased mechanical strength [12]. The effective interaction of concrete materials results in the uniform distribution of conventional and filler materials. There were no capillary variations in this concrete cube block. The pattern of concrete peaks of basic (111), (200), (220), and (221) were even. Moreover, the XRD analysis.

3.2. The compressive strength of developed concretes

Here, three concrete cubic blocks from each concrete were evaluated. The average of three is considered compressive strength after 28 and 90 days of the curing process, as shown in Fig. 4.

It was shown that the concrete developed without alumina, silica fume, and kaolin waste (CC1) was lower than the compressive strength of alumina, silica fume, and kaolin waste-developed concrete blocks. The compressive strength of CC1 concrete showed 28 ± 1.4 MPa during the 28-day curing process. At the same time, the inclusions of 5% alumina and 10% kaolin waste blended with conventional concrete found a 21.4% improvement in compressive strength compared to CC1 concrete. The inclusions of kaolin waste could withstand the maximum compressive load without crack propagation [35].

The concrete developed with 5, 10, and 15% silica fume along with 5% alumina and 10% KW showed a significant improvement in compressive strength, and CC5 concrete contained 5% Al_2O_3/10%KW/15% SF recorded maximum compressive strength of 41 ± 1.23 MPa. However, it was noted from Fig. 4 that the compressive strength of concrete cured within 90 days was larger than that of concrete cured within 28 days. The concrete cured with 90 days of CC1 showed 29 ± 1.16 MPa, and adding 5% alumina/10KW in concrete showed a 17.24% improvement in compressive strength compared to CC2. Further additions of SF as 5, 10, and 15% recorded higher compressive strength than CC1 and CC2. It was because curing action and alumina could offer the maximum resistance force against the compressive load [34,39]. However, the CC5 (5% alumina/10% KW/15% SF) concrete cured with 90 days showed the maximum compressive strength and hiked by 7% and 51.72% compared to 28 days cured CC5 and 90 days cured CC1. The effective binding action of Portland cement with their mixer is the reason for the highest maximum compressive strength. Its effective binding of Portland cement with cement paste peaks with their aggregates is evidenced in Fig. 3. In addition, the compressive strength (gain) of concrete has been enriched due to the water absorption percentage is reduced and evidenced in Fig. 6. However, increased water absorption may lead to void results crack propagation [34]. Moreover, this CC5 concrete, compared to the previously reported result [35], was increased by 15.78%.

3.3. Flexural strength of developed concretes

Fig. 5 indicates the bar chart illustration of concrete prepared with different percentages of Portland cement, fine sand, coarse aggregate stone crush, water, alumina, kaolin waste, and silica fume is addressed in Table 2

It was evaluated after the 28 and 90 days curing process. Here, the graph of Fig. 5 proves the significance of the curing process. It was observed from Fig. 5 that the flexural strength of concrete showed a progressive improvement due to the additions of silica fume at 0, 5, 10, and 15 %, respectively. The flexural strength of CC1 concrete (cured by 28days) showed 3 ± 0.15 MPa and increased by 23.3% on adding 5% Al_2O_3/10% KW (CC2). The flexural strength enhancement was due to 10% KW instead of gravel stone. The mining kaolin waste has great potential for high load-carrying capacity with good mechanical behavior [35]. Here, the additions of SF as 5, 10, and 15% showed progressive improvement, and CC5 concrete (5%Al_2O_3/10KE/15%SF) recorded maximum compressive strength (4.2 ± 0.13 MPa) and raised by 40% compared to CC1 concrete.

Moreover, the concrete cured within 90days was found to have a higher flexural strength value than the 28-day-cured concrete cubes. It results in increased durability of concrete [36]. The flexural strength of CC1 concrete (cured within 90days) was improved by 10% compared to CC1 concrete cured within 28days. While the flexural strength of CC2, CC3, CC4, and CC5 showed the improvement

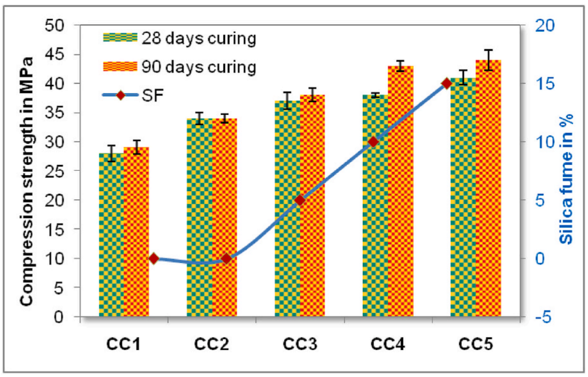


Fig. 4. Compressive strength of developed concrete under 28 and 90days curing process.

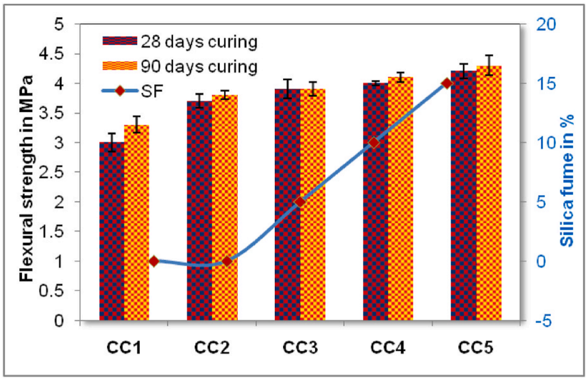


Fig. 5. Flexural strength of developed concrete under 28 and 90days curing process.

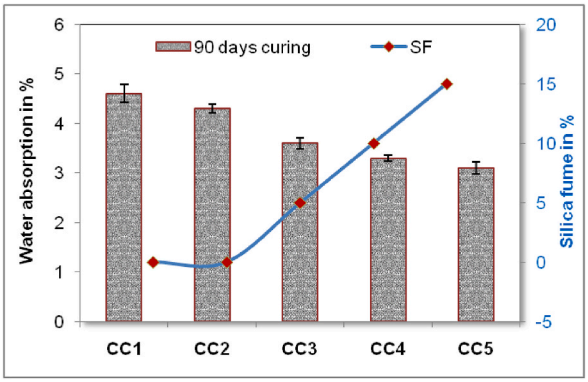


Fig. 6. Water absorption behavior of developed concrete after the 90days curing process.

of 15.15%, 18.1%, 24.2% and 30% compared to CC1 concrete. The induction of concrete flexural strength is the reason for effective binding action between cement paste and their mixtures. It is provided that well-adherence behavior improves flexural strength gain and restricts the aggregate displacement during higher loading. The enhancement of flexural strength was due to the homogenous mixture of concrete making an effective interfacial bonding strength was evidenced in XRD peaks Fig. 3

3.4. Water absorption behavior of developed concretes

Fig. 6 represents the water absorption percentage of concrete prepared with 5% of Al_2O_3/10KW and 5, 10, and 15% of SF compared to conventional concrete cube blocks. The water absorption percentage of CC1 concrete containing ordinary Portland cement, fine sand, and coarse aggregate gravel was 4.6 ± 0.18%. Adding 5% alumina and 10% KW in CC1 reduced water absorption percentages of 4.3 ± 0.08%. The mining waste blended with conventional concrete offered good water absorption resistance [35]. However, the additions of silica fume in the conventional concrete mixed with 5% alumina and 10KW were found to be 3.6 ± 0.10%. Further additions of SF in concrete offered good water absorption behavior and maintained their limit of less than 5% [37]. The waster absorption percentage for CC4 and CC5 was 3.3 ± 0.06% and 3.1 ± 0.12% respectively. The enhancement of water absorption resistance was due to silica fume and fine aggregated sand particles in a concrete mixture [1,38]. In addition, CC5 concrete was found to have minimum water absorption, lower than the allowable limit of 5% [39].

However, the impact of silica fume mixture on developed concrete is exposed to a better relationship between the water absorption

Table 3
Reduction in concrete weight and compressive strength percentage after acid behavior evaluation.

Concrete mixing design (Test Concrete cube)	Compressive strength in MPa		Reduction in concrete weight	Reduction in compressive strength
	Water curing	Sulfuric Acid Curing		
	After 90days		%	%
CC1	29 ± 1.6	24 ± 1.2	1.7	17.24
CC5	44 ± 1.7	38 ± 1.1	0.78	13.63

behavior is indirectly proportional to compressive/flexural strength gain of concrete. This is evidenced in Figs. 4–6 above. At the same time, the higher moisture absorption facilitates void/porous inside the concrete, resulting in reduced compressive and flexural strength of concrete [37].

3.5. Acid behavior studied of developed concrete

Based on the mechanical performance, the 90-day cured CC1 and CC5 concrete was chosen as an acid behavior study. Table 3 shows the concrete's weight reduction and compressive strength percentage after the acid behavior study.

It was noted from Table 3 that the compressive strength of CC1 cured with water for 90days showed 29 $\pm$ 1.6 MPa and a reduction in weight of 1.7% with a reduced compressive strength of 24 $\pm$ 1.2 MPa. It was due to the sulfuric acid curing process. Similarly, the CC5 concrete contained 15% SF showed a 13.63% reduced compressive strength, which is higher than the value of CC1 and its weight was reduced by 0.78% due to the presence of alumina resist to sulfide chemical reaction during the acid curing process and recorded by 0.78% reduction in weight compared to water curing CC5 concrete. Moreover, the curing of sulfuric acid leads to deterioration of compressive strength due to the impact of chemical attack; this depends on the composition, structure, and hydration of the material in the concrete. Here, the strength gains compressive strength gain is decreased on sulfuric acid curing, as shown in Table 3 above. Likewise, the strength gain for flexural may lead to a downtrend in sulfuric acid curing; its details are exposed in Table 4 as follows.

With the processing, sulfuric acid curing is exposed to reduced flexural strength and noted by its flexural strength of CC1 and CC5 are 3.3 $\pm$ 0.15 and 4.3 $\pm$ 0.1 MPa. Its reduction flexural strength was 15.15 and 18.6%, respectively.

This current investigation results in CC5 concrete containing 5% alumina,10% kaolin waste, and 15% silica fume, which exploited superior mechanical properties. Its results are compared with past literature in Table 5. The CC5 concrete's compressive strength is hiked by 15.7% of concrete with 20% glass powder, 5% metakaolin, 15% silica fume [35] and 18.9% of Concreter with 8% silica fume/27% fly ash [43]. Likewise, the CC5 concreter is exposed to superior flexural strength and attained a 20.78% hike related to the flexural strength of concrete with 6% Basalt fiber and 10% crumb rubber [36], and water absorption behavior is limited by 29% and its value related to Concrter with 10% zeolite, and 10% metakaolin [41,42].

4. Conclusions

With the exposures of present research of concrete was successfully prepared with and without alumina (5%), kaolin waste (10%) and 0, 5, 10, and 15% of silica fume, and its results showed superior mechanical, water absorption, and acid behavior values. The kaolin waste (KW-10%) and 0, 5, 10, and 15 % silica fume were effectively incorporated with the concrete mixture to replace gravel stone and fine sand partially. The following results are highlighted in the key points.

- Amid the various combinations of concrete mixture, the 5% alumina/10KW/15SF (CC5) facilitated better compressive/flexural characteristics than the CC1 concrete (without alumina/KW/SF) under cured by 90days.
- The compressive strength of 5% alumina/10KW/15SF concrete (CC5) hiked by 51.72% in the contest of CC1 concrete (without alumina/KW/SF). Similarly, this concrete exposed superior flexural strength and attained a 30.3% improvement compared to the CC1 concrete structure, cured by 90days.
- The XRD image peaks revealed a homogenous mixture design (even peaks) with effective binding action with cement paste that facilitated good mechanical characteristics.
- The 5% alumina/10KW/15SF concrete (CC5) found a reduced water absorption percentage of 32.6%. It is better than the water absorption behavior of CC1.
- In addition, the acid behavior of concrete developed with 5% alumina, 10KW, and 15% SF showed a limited weight reduction of 0.78% compared to CC1 concrete.

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No funding was used for this study.

Data availability

All the data required are available within the manuscript.

CRediT authorship contribution statement

Anandh Babu Malayali: Funding acquisition, Formal analysis, Data curation, Conceptualization. **Venkatesh R:** Writing – review & editing, Writing – original draft. **Sulaiman Ali Alharbi:** Resources, Project administration, Methodology, Investigation. **M.A. Kalam:** Visualization, Validation, Supervision, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

Table 4
Reduction in concrete weight and flexural strength percentage after acid behavior evaluation.

Concrete mixing design (Test Concrete cube)	Flexural strength in MPa		Reduction in concrete weight	Reduction in flexural strength
	Water curing	Sulfuric Acid Curing		
	After 90days		%	%
CC1	3.3 ± 0.15	2.8 ± 0.11	1.7	15.15
CC5	4.3 ± 0.1	3.5 ± 0.12	0.78	18.6

Table 5
Present work compared with past literature.

S.No	Descriptions	Compressive strength	Flexural strength	Water absorption	Ref.
		MPa	MPa	%	
1	Concrete with 20% glass powder, 5% metakaolin, 15% silica fume	38	–	–	35
2	Concrete with 6% Basalt fiber and 10% crumb rubber	38.3	3.56	–	36
3	Concrete with 10% zeolite and 10% metakaolin	29	–	2.4	41
4	Concreter with 10% of metakaolin	–	3.5	7.82	42
5	Concreter with 8% silica fume/27% fly ash	37	–	<4	43
6	Concrete with 5% alumina,10% kaolin waste, and 15% silica fume	44	4.3	3.1	Present

influence the work reported in this paper.

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