SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V12I11P111

Volume 12 Issue 11, 132-144, November 2025

Original Article

Sustainable Concrete Development Using Desert Sand and Metakaolin: Mechanical and Durability Assessment

Jash P. Joshi[1], Ashish D. Kachhadiya[2], Prashant K. Bhuva[3], Shekhar H. Parmar[4], Chirag R. Odedra[5]

[1]*Pacific Construction Services LLC, Chicago, IL, USA.*
[2,3,4,5]*Department of Civil Engineering, Dr. Subhash University, Junagadh, Gujarat, India.*

[2]*Corresponding Author : ashish.kachhadiya@dsuni.ac.in*

Received: 07 September 2025 Revised: 08 October 2025 Accepted: 06 November 2025 Published: 29 November 2025

Abstract - *The deficit of natural river sand and the ecological impact of cement production have elevated the demand for eco-efficient materials for concrete production. The present research investigates the combination of Desert Sand (DS) and Metakaolin (MK) as a sustainable source of natural fine aggregate and cement in M25 concrete. Desert sand sourced from the Kachchh region of Gujarat, India, was utilized to substitute fine aggregate at proportions of 10%, 20%, and 30%, while metakaolin was integrated at 5%, 10%, and 15% replacement of cement. The mechanical parameters, comprising compressive, flexural, and split tensile strength, as well as durability against acid and sulphate attacks, were assessed at 7 and 28 days. The findings reveal that the specimen with 20% DS and 10% MK (Sample S5) had the maximum compressive strength of 32.89 MPa at 28 days, in addition to enhanced flexural and tensile strength relative to the control mix. Improved acid and sulphate resistance was also noted, signifying enhanced durability. The findings indicate that desert sand and metakaolin can be effectively employed to create durable, high-performance concrete appropriate for dry and coastal areas. This integrated method promotes sustainable material use and diminishes reliance on river sand.*

Keywords - *Desert sand, Metakaolin, Sustainable concrete, Compressive strength, Durability, Acid resistance, Sulphate resistance.*

1. Introduction

Concrete is frequently used material in modern infrastructure. Desert sands are abundant in arid and semi-arid regions such as Gujarat and Rajasthan; however, there is limited research to demonstrate how this material is effective like sand in structural concrete. Prior research has suggested that DS will have a relatively smaller particle size and increased passer content, which are both variables that can have a direct effect on workability and strength. Supplementary cementitious materials, most notably Metakaolin (MK), have demonstrated improvements in both strength and durability through pozzolanic reaction and refining pore structure.

1.1. Research Gap

Much research has looked at wasteland sand and metakaolin on my own; however, not many have checked out how they work collectively in concrete, in particular in relation to how sturdy and long-lasting they are under harsh conditions.

Most cutting-edge studies focus in particular on compressive power, acid and sulfate resistance, in addition to thorough microstructural investigations.

1.2. Research Objective

This study aims to prepare a concrete mix that is environmentally friendly by using desert sand and MK as a partial replacement for sand and cement, respectively. The trial program assesses their overall effect on workability, compressive strength, tensile strength, flexural strength, and resistance to acid and sulphate attack in M25 concrete.

2. Literature Review

Many studies have been carried out on how to make concrete more environmentally friendly by adding desert sand and Luo et al. [1] showed that desert sand can be used as a replacement of sand without weakening the concrete's mechanical strength, as long as the sand-to-cement ratio is kept controlled sand can be used as a fine aggregate without weakening concrete's mechanical strength, as long as the sand-to-cement ratio is kept controlled.

Al-Harathi et al. [11] similarly indicated that sand can replace up to 50% of river sand in conventional concrete while maintaining adequate workability and compressive strength. Nevertheless, these investigations raised concerns about the increased chloride and silt content of desert sands, which could affect long-term sustainability.

Researchers have considered using Metakaolin (MK) to gain strength and durability. Dinakar and Manu [4] found that adding metakaolin to HS-SCC made it stronger in both compression and tension because metakaolin is very reactive. Zari et al. [20] and Gunasekaran et al. [21] MK was also found to made materials more resistant to chloride and less permeable, making it good for harsh conditions.

Recent studies have investigated hybrid systems that integrate desert sand with mineral mixtures; Nevertheless, overall valuations are still low. Kaufman [3] looked at desert sand mixed with calcium sulfoaluminate cement and found that it had good mechanical properties. Kannan and Ganesan [13] showed that is more resistant to acid, but the amount of replacement made a difference in how well it performed. But not much research has looked at how both metakaolin and desert sand work together when used in regular concrete.

2.1. Research Gap

Current literature shows the individual effect of desert sand and metakaolin; Nevertheless, their synergistic effects on concrete's mechanical performance and durability have not yet been fully investigated. Most previous studies only looked at how strong the materials were, and did not compare how well they resisted acids and sulfates or find the best replacement conditions.

This study intends to fulfill this gap through a systematic examination of the synergistic effects of DS and MK on M25 concrete's mechanical and durability properties, while also offering fresh experimental data to support the use of sustainable materials in construction in arid areas.

The reported test trends apply just to the specific type of desert sand examined. The optimization of VFP content in DSC for dune sand from various deserts should rely on trial mixtures [1].

The study examines a new approach, which integrates desert sand with a binding machine composed of Calcium Sulfo-Aluminate cement (CSA) and plaster to achieve optimal work qualifications and packaging density, thus facilitating a significant sand replacement ratio in traditional concrete [2, 3].

The CSA/plasterboard used in this context was adapted to provide a high ettringite content so that it could mix a significant amount of water during hydration. CSA content in concrete can decrease when the model increases the mechanical capabilities of CSA/plaster binder when combined with the desert's sand.[3].

This work utilises metakaolin as a highly reactive addition, showing significant potential for improving concrete composites. [20].

The analysis decided that the use of already established efficiency values for metakaolin, self-sized designed with proposed function, metakaolin concrete with continuous cement content of 550 kg/m3 can receive all metakaolin percentages (7.5%, 15%, 22.5%) with exhausted forces (80, 100, and 120 MPA) [21].

The study examines the relevant materials characteristics of Havsand, Desert Sand, and Elves. Cement mortar blocks were produced using varying amounts of fine aggregate materials. After curing for 3, 7, 28, and 56 days, the blocks were tested for compressive strength. [5].

The analysis found that the Marin Sand sample from Malpe beach is of high quality and that all other important qualities are within acceptable limits. [6].

The study examined several water-to-sea metakaolin conditions of 0.32, 0.35, 0.4, and 0.5. The MK ratio was adjusted from 0% to 15% in a 5% increase, and the age 3 to 90 days was investigated, with properly operated experiments. The data indicate that MK's enlargement of strength is only important in the early stages, while long-term strength growth is insignificant [22]. The increase in the compressed force of MK-concrete was significantly higher for water-cement conditions, making it more suitable for high weight/cm conditions. MK is more impressive in reduced cooloms, so chloride increases the penetration resistance in early stages. Inclusion of MK affects significant chloride permeability, preparedness at the level of compensation, and the age of concrete. In this amount of compensation, the Coulomb values are reduced from 86% to 94% at 0.32 weight/cm by 15% mk. [7].

In order to assess the feasibility of using granulated copper slag as a mineral ingredient for large-scale concrete in saline-soil situations, this study will conduct experiments. [8]. The study concluded that the properties of cement mixed with granulated copper slag were similar to those of Fly Ash, which substantially reduced the heat of hydration. Moreover, the secondary heat development peaks of samples incorporating granulated copper slag were somewhat shifted to the right relative to the plain cement sample and the Fly Ash cement samples. The mechanical strength and chloride ion permeability of granulated copper slag concrete under TMC circumstances surpassed those observed under traditional curing conditions [9].

In comparison to the concrete that contained Maowusu sandy normal sand, the concrete that contained Tenggeli desert sand demonstrated superior workability. The former had a higher degree of cohesion, but it had a lower fluidity percentage. When it comes to civil engineering, it is possible to use concrete that contains desert sand as a fine aggregate [10].

This study reports the conclusions from a study of the properties of Sandbetong. Different control combinations of the use of regular Portland cement were designed to meet the minimum criteria for compressed strength of 40 N/mm. About 36% of the total sets were formed by the weight of the total set. The laborability varies from at least 16 mm to a maximum of 122 mm. For each control mixture, a replacement mixture was made by responding to the fine set of different quarters of dark, from 10% to 100%. Five separate control mixtures were made, each designed to achieve a compressed power of 40 MPa.

The work capacity as an evaluation with a downturn varies from a minimum of 16 mm to a maximum of 122 mm. However, this decline was minimal, with the largest decline in strength about 25%. In addition, for example, the ratio of sand to sand increases the absorption of the surface of the concrete. At the low percentage of dunes, the surface absorption of variation in sleeping sand material is affected. In the mixture with elevated sand material, the absorption of the surface was maximized. Increasing the TIBBA sand content does not destroy the modulus of elasticity and tensile force to a large extent. This study indicates that the TIBBA sand can serve as a fine set in fixed yogas when suitable sand sources are not easily commercially available [11].

The letter describes a study that uses traditional Portland cement according to IS 8112-1989, corresponding to the fine and thick set of IS 383 (2011), as well as GGB and Metacolin. The ingredients used include suppressing 20%, 30%, 40%and 50%of the cement weight individually with GGB and metacoline. [12, 24].

The study concluded that the compressed force of concrete with 20% metacoline and 10% GGB replacement of 28 days overhaul normal concrete [21]. Compressed force of concrete with 10% GGB replacement is higher than the usual concrete, after which it drops, while metacolin produces up to 20% replacement, with 20% provides better tensile strength than traditional concrete. The divided tensile power of concrete with 10% GGB replacement is better, while 20% metacolin compensation provides more tensile strength than regular concrete. However, GGB performs with subordinate tensile strength compared to regular concrete, while better tensile force compared to traditional concrete resulted in compensation for metacolin, a result of 15% to 20%. Flexible strength of concrete containing 10% GGB and 20% metakaolin replacement, overhauling normal concrete [6]. This study examines the sturdiness features of MK and RHA in a 1:1 ratio, even as discussing their interrelationships [25]. The sturdiness characteristics of the unique mixtures had been examined [7].

Research indicates that you can make concrete with Adding 30% MK to blended SCC mixtures makes them more electrically conductive and permeable than unblended SCC. The SCC and MK did not work well together in an acidic environment. The compressive strength of SCC with RHA is not as good as that of SCC with MK when 30% of the mix is replaced, but it is much more durable, especially against acid attacks [13].

This study gives a comparative experimental investigation of bricks composed of barren region sand and metakaolin vs those produced from fly ash and Portland cement. Desert sand and metakaolin are covered in various proportions to fabricate the brick, with their weights expressed as a percentage of the brick's general weight [14].

The experimental study established that there is no change in the size, structure, or shape of the bricks after the curing phase, which reflects their usability for construction. Bricks made with the use of metakaolin as a binder have a significant rise in density in comparison to those made with the use of cement, thus improving compressive strength and material durability. The density of desert sand brick has risen by 45% as opposed to fly ash brick. A rise in density means a rise in the hardness of the brick [15].

This research investigates, develops, and evaluates the effectiveness of using steel fiber reinforced concrete to a mix with natural coarse aggregates [16]. The incorporation of steel fibre has increased early-age compressive strength, although it has constrained the progression of the hydration process. The replacement of RCA significantly affected compressive strength more than the incorporation of steel fibres, as the reduction in strength from RCA counteracted the strength enhancement provided by the fibres. [17].

3. Summary of Literature Survey

The literature review shows that DS can be used as an alternative source of fine aggregate, and research shows that, it is more suitable for compressive strength. But desert sand contains some amount of chloride content, which is harmful for the concrete durability and steel reinforcement [19]. The effect of chloride in concrete can be reduced by using some mineral admixture [19]. In this research, metakaolin is used in different percentages for the chloride resistance; from the research paper, it was found that 10% to 30% MK is used with different materials in different contents, and it is concluded that 8% to 15% MK with desert sand provides greater chloride resistance of concrete. Some research shows that how metakaolin reacts with binder material changes the ideal properties of concrete. So this study is about to use MK in 5%, 10%, & 15% and DS in 10%, 20%, 30% in my research work.

4. Additive in Concrete Mix

4.1. Metakaolin

- Metakaolin is a highly reactive pozzolan produced from China clay. It must undergo a combustion process similar to cement.
- Metakaolin Chemical Properties

Table 1. Metakaolin chemical properties

Chemical Properties	Value
Silica (SiO2)	47.00% ± 0.50%
Alumina (Al2O3)	48.00% ± 0.50%
Ferric oxide Calcium oxide (Fe2O3)	00.85% ± 0.10%
Calcium oxide + Magnesium oxide (Cao + MgO)	00.50% ± 0.05%
Titanium dioxide (TiO2)	01.25% ± 0.10%
Sodium oxide + Potassium oxide (NA2O + K2O)	00.35% ± 0.10%
Loss on ignition	00.80% ± 0.05%

Fig. 1 Metakaolin

Fig. 2 Desert sand

4.2. Desert Sand

- Gujarat and Rajasthan are part of the Aolian Sands, India's great Indian Thar Desert, and attract tourists mainly in India and around the world.
- Nevertheless, the increasing demand for countries for infrastructure development - which includes housing, commercial, and strategic functions - requires their stabilization.
- In addition, there is an urgent need to use these aolian sands as a building material, due to a significant reduction of sand, which requires compulsory characterization of their extensive characteristics.
- In general, these sands show the properties of aolian sand from the Arabian Peninsula, Australia, and China.
- In addition, to use these sands in the construction sector, especially in concrete and mortar as a fine unit.

5. Research Methodology

The research design was implemented to assess the mechanical properties and durability of M25 concrete with Desert Sand (DS) and Metakaolin (MK).

Concrete mixes containing the control and modified variants were made, and the workability, compressive strength, flexural strength, split tensile strength, and durability to acid and sulphate attack were determined.

5.1. Materials Used

5.1.1. Cement

Ordinary Portland Cement.

5.1.2. Fine Aggregate

River sand from the local source and Desert sand

5.1.3. Coarse Aggregate

Crushed granite aggregate

5.1.4. Metakaolin (MK)

A high-reactivity pozzolanic material produced from calcined kaolinite clay at 750–800 °C.

5.1.5. Water

Tap water

5.2. Mix Design and Rationale

The concrete mix design for M25 grade was prepared as per IS 10262:2019 guidelines. The control mix proportion was finalized with a water-to-cement ratio (w/c) of 0.4, giving a target mean strength of 31.6 MPa.

To examine the influence of DS and MK, replacements were made at the following levels:

5.2.1. Desert Sand (DS)

10%, 20%, and 30% of fine aggregate.

5.2.2. Metakaolin (MK)

5%, 10%, and 15% of cement.

The selection of these replacement percentages was based on findings from previous studies [4, 7, 11, 20], which indicated that DS up to 30% and MK up to 15% provide optimum strength without compromising workability.

As per IS code, here for this study, concrete of M25 grade is used, so the mix design of M25 grade is as follows,

Table 2. Concrete mix design of M25 grade

	Water (lit)	Cement (kg)	F.A. (Sand) (kg)	C.A. (Aggregate) (kg)
For 1 m^3	197	492.5	673.66	1147.26
For 1 kg of cement	0.4	1	1.368	2.33
For 1 bag of cement	20	50	68.4	116.5

5.3. Experimental Setup

All concrete specimens were mixed using the laboratory pan mixer with a 40 L capacity. The concrete is placed in steel molds and vibrated with a table vibrator. Curing was done in a water tank at 27 ± 2 °C.

Testing Instruments:

Workability: Tested by the Slump Cone Apparatus

Compressive Strength: Tested by a Compression Testing Machine (CTM) of 2000 kN

Flexural Strength: Tested by Flexural Testing Machine

Split Tensile Strength: Performed on cylindrical specimens

Durability Tests: For sulfate attack, cubes were submerged in 5% $MgSO_4$ solution for 28 days; acid attack was observed in cubes submerged in 5% HCl solution for 28 days and tested for compressive strength.

5.4. Statistical Analysis

To assess the significance of differences across different DS–MK combinations. The ANOVA test showed that replacement levels had a statistically significant impact ($p < 0.05$) on the compressive strength, thereby confirming that the compressive strength increase for the S5 mix (20% DS + 10% MK) was not due to random variation, but a consequence of material synergy.

5.5. Summary

This experimental framework provides a reliable basis for understanding the combined influence of desert sand and metakaolin on the physical and durability properties of concrete.

6. Experimental Methodology

The following are the tests planned to carry out on prepared concrete.

Table 3. Number of cubes to be cast

Specimen No.	Desert Sand	Meta-kaolin	No. of Cube		Cubes for Sulphate Attack	Cubes for Acid Attack	Total Cubes for each specimen
			7 days	28 days			
S	0%	0%	3	3	3	3	12
D1	10%	0%	3	3	3	3	12
D2	20%	0%	3	3	3	3	12
D3	30%	0%	3	3	3	3	12
S1	10%	5%	3	3	3	3	12
S2	10%	10%	3	3	3	3	12
S3	10%	15%	3	3	3	3	12
S4	20%	5%	3	3	3	3	12
S5	20%	10%	3	3	3	3	12
S6	20%	15%	3	3	3	3	12
S7	30%	5%	3	3	3	3	12
S8	30%	10%	3	3	3	3	12
S9	30%	15%	3	3	3	3	12
Total cubes							156

Table 4. Number of beams & columns to be cast

Specimen No.	Desert Sand	Meta-kaolin	No. of beam & Cylinder	
			for flexural test	for flexural test
S	0%	0%	2	2
D1	10%	0%	2	2
D2	20%	0%	2	2
D3	30%	0%	2	2
S1	10%	5%	2	2
S2	10%	10%	2	2
S3	10%	15%	2	2
S4	20%	5%	2	2
S5	20%	10%	2	2
S6	20%	15%	2	2
S7	30%	5%	2	2
S8	30%	10%	2	2
S9	30%	15%	2	2
Total Beams & Cylinders			2	2

Fig. 3 Cube specimen

Fig. 4 Beam & cylinder specimen

7. Discussion with Results

The results of all mixes were analyzed DS and MK on the workability, compressive strength, flexural strength, split tensile strength, and durability characteristics of M25 concrete. Figures 5-13 illustrate the trends graphically, accompanied by the numerical data presented in Tables 5-11.

7.1. Workability Result

In Table 5 and Figure 5, the slump values suggest that workability improved with greater DS and MK content. The highest slump value (115 mm) was measured for Specimen S9, which was made with 30% DS and 15% MK. Given the fine particle size of DS and the lubricative nature of MK, the Slump value indicates better fluidity. Similar trends were observed in the literature by Luo et al. [1] and Liao et al. [7], where desert sand also improves packing density when proportioned correctly.

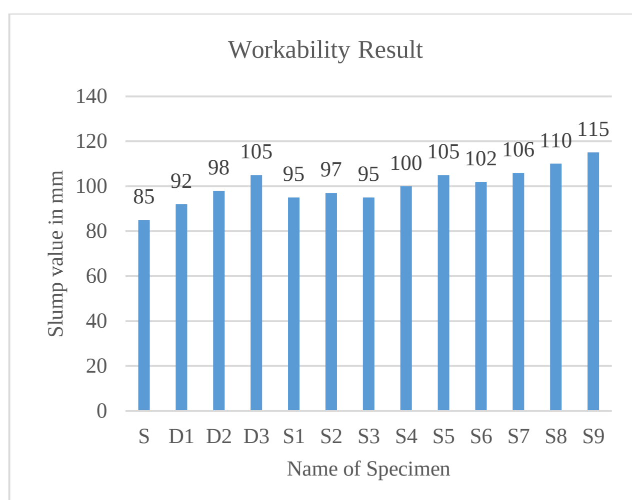

Fig. 5 Graph of workability value result

Table 5. Workability Result

Sr. no.	Name of Specimen	% of desert sand	% of natural sand	% of Metakaolin	Slump value in mm
1	S	0%	100%	0%	85
2	D1	10%	90%	0%	92
3	D2	20%	80%	0%	98
4	D3	30%	70%	0%	105
5	S1	10%	90%	5%	95
6	S2	10%	90%	10%	97
7	S3	10%	90%	15%	95
8	S4	20%	80%	5%	100
9	S5	20%	80%	10%	105
10	S6	20%	80%	15%	102
11	S7	30%	70%	5%	106
12	S8	30%	70%	10%	110
13	S9	30%	70%	15%	115

7.2. Compressive Strength Value

The results for compressive strength obtained (Tables 6, and 7, Figure 6, and 7) showed clear strength improvements as mixing ratios increased up to 20% DS and 10% MK (sample S5). The increased strength is attributed to the pozzolanic activity presented by MK, which densifies pore structure and develops interfacial bond strength between paste and aggregate. The ANOVA results to test variation between mixes were statistically significant ($p < 0.05$). These findings are consistent with Zareei et al. [20] and Gunasekaran et al. [21], who also noted strength gains with MK of 5-10%.

7.2.1. Compressive Strength Result after 7 days

Table 6. Compressive strength after 7 days

Sr. no.	Name of Specimen	No. of Cube			Compressive strength after 7 days in N/mm2
		1	2	3	
1	S	19.78	19.11	20.89	19.93
2	D1	21.11	19.56	20.89	20.52
3	D2	18.89	20.00	19.33	19.41
4	D3	18.67	20.22	20.67	19.85
5	S1	22.22	21.56	22.89	22.22
6	S2	23.11	22.00	22.89	22.67
7	S3	21.78	22.89	21.56	22.07
8	S4	25.33	22.22	23.33	23.63
9	S5	24.44	22.89	25.11	24.15
10	S6	21.78	20.00	22.67	21.48
11	S7	21.33	22.44	20.44	21.41
12	S8	22.22	21.56	20.89	21.56
13	S9	21.33	20.44	23.11	21.63

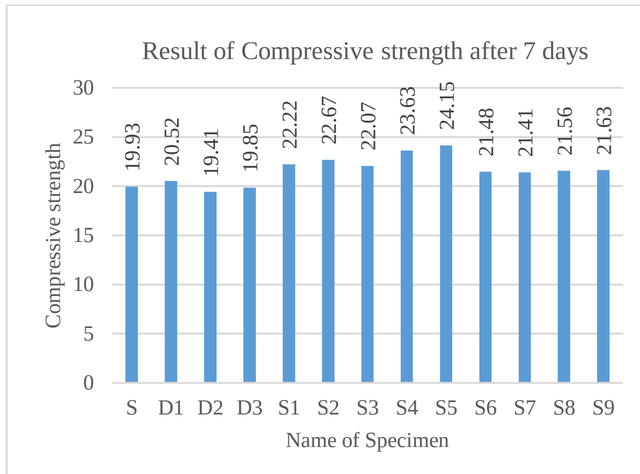

Fig. 6 Graph of the compressive strength after 7 days

7.2.2. Compressive Strength Result after 28 days

Table 7. Result of compressive strength after 28 days

Sr. no.	Name of Specimen	No. of Cube			Observed Compressive Strength after 7 days in N/mm2
		1	2	3	
1	S	32.89	30.67	31.78	31.78
2	D1	32.22	30.89	33.33	32.15
3	D2	29.78	31.11	30.44	30.44
4	D3	29.11	30.22	27.56	28.96
5	S1	31.56	30.22	32.89	31.56
6	S2	28.44	29.56	27.56	28.52
7	S3	26.67	26.00	27.78	26.81
8	S4	32.00	32.44	33.33	32.59
9	S5	32.89	33.56	32.22	32.89
10	S6	30.22	28.89	30.89	30.00
11	S7	32.00	30.89	33.33	32.07
12	S8	28.89	30.22	31.78	30.30
13	S9	27.78	30.22	28.89	28.96

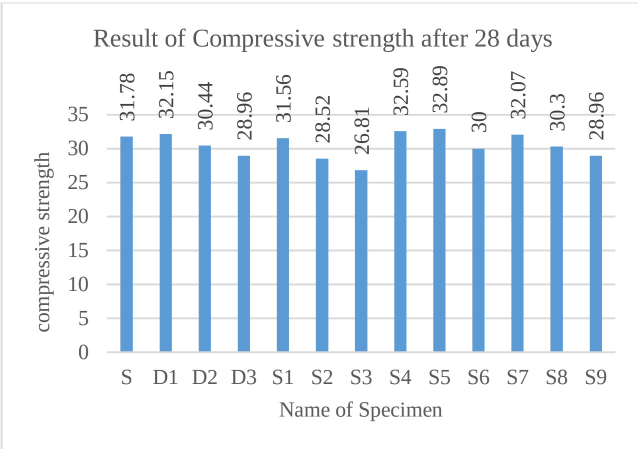

Fig. 7 Result of compressive strength after 28 days

7.3. Flexural Strength Test

Once again, the flexural strength results (Table 8, Figure 8) were similar to the load-bearing capacity, where moderate levels of DS and MK improved the load-bearing capacity of concrete beams. The S5 mix produced a 3.70 MPa average flexural strength, which was a little more than 8% greater than the control specimen. This strength improvement is likely attributable to improved interlocking at the interfacial transition zone between fine DS particles and the matrix found by Al-Harthy et al. [11]

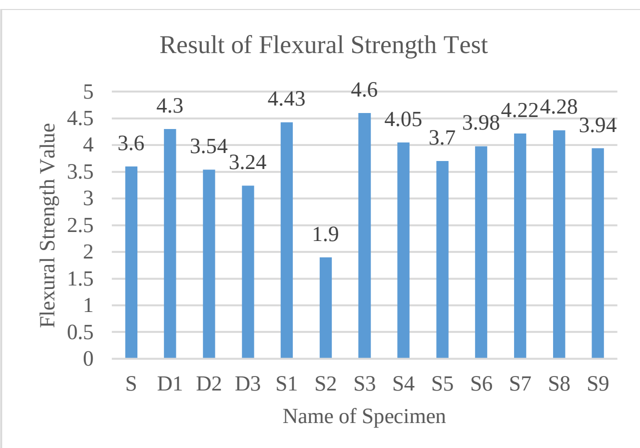

Fig. 8 Graph of result flexural strength test

Table 8. Test Result of Flexural Strength

Sr. no.	Name of Specimen	No. of Beams		Flexural Strength
		1	2	
1	S	3.40	3.80	3.60
2	D1	4.40	4.20	4.30
3	D2	3.60	3.48	3.54
4	D3	3.20	3.28	3.24
5	S1	4.60	4.25	4.43
6	S2	0.00	3.80	1.90
7	S3	4.70	4.50	4.60
8	S4	4.00	4.10	4.05
9	S5	3.75	3.65	3.70
10	S6	4.03	3.93	3.98
11	S7	4.25	4.19	4.22
12	S8	4.95	3.62	4.28
13	S9	4.10	3.78	3.94

7.4. Split Cylinder Strength Test

The split tensile strength results (Table 9, Figure 9) also improved for mixes that included 10% to 20% DS with either 5% or 10% MK. The S5 mix achieved a strength of 3.79 MPa, reflecting an increase in cohesion and bond strength within the concrete matrix. Increased MK (over 15%) caused a decrease in tensile strength due to brittle behavior, corroborating the findings of Dinakar and Manu [4].

Table 9. Split cylinder strength test

Sr. no.	Name of Specimen	No. of Beams		Tensile Strength
		1	2	
1	S	2.97	3.61	3.29
2	D1	2.12	2.90	2.51
3	D2	3.47	3.25	3.36
4	D3	4.10	3.61	3.86
5	S1	3.18	3.33	3.25
6	S2	2.55	3.04	2.79
7	S3	3.11	2.83	2.97
8	S4	4.10	3.33	3.71
9	S5	3.96	3.61	3.79
10	S6	3.11	3.54	3.33
11	S7	4.03	2.76	3.40
12	S8	3.54	3.04	3.29
13	S9	3.33	3.47	3.40

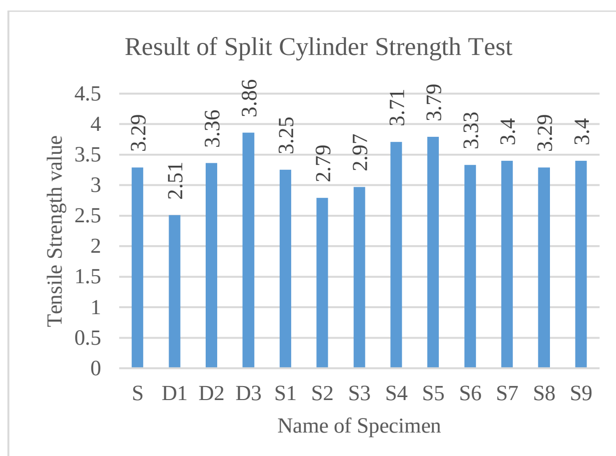

Fig. 9 Graph of result of the split cylinder strength test

7.5. Durability Test: Acid and Sulphate Resistance Test

Durability testing (Tables 10, and 11, Figure 10, and 11) indicated that DS–MK combinations improved resistance to sulphate attack and acid. For the acid attack, the compressive strength of S5 after 28 days of acid exposure showed the least loss in compressive strength (almost 9% loss), while the control concrete suffered about 17% loss in compressive strength. Similarly, sulfate resistance improved, where the compressive strength of S5 retained 90% of its original compressive strength. This shows that MK decreases permeability and provides better resistance to chemical attack by utilizing calcium hydroxide and forming additional C–S–H gel. Comparable behavior was reported by Kannan and Ganesan [13].

7.5.1. Acid Attack Durability Observation

Table 10. Acid attack durability observation

Sr. no.	Name of Specimen	No. of Cube			Compressive strength after 56 days in N/mm2
		1	2	3	
1	S	26.22	25.56	27.11	26.30
2	D1	26.89	27.56	26.22	26.89
3	D2	29.11	27.11	25.56	27.26
4	D3	27.56	26.00	25.56	26.37
5	S1	29.78	27.56	28.44	28.59
6	S2	18.44	20.22	21.11	19.93
7	S3	23.78	22.22	21.56	22.52
8	S4	23.33	24.44	23.78	23.85
9	S5	22.22	24.67	25.33	24.07
10	S6	21.11	22.67	21.78	21.85
11	S7	27.56	26.67	28.22	27.48
12	S8	26.67	26.00	27.56	26.74
13	S9	26.89	24.67	25.78	25.78

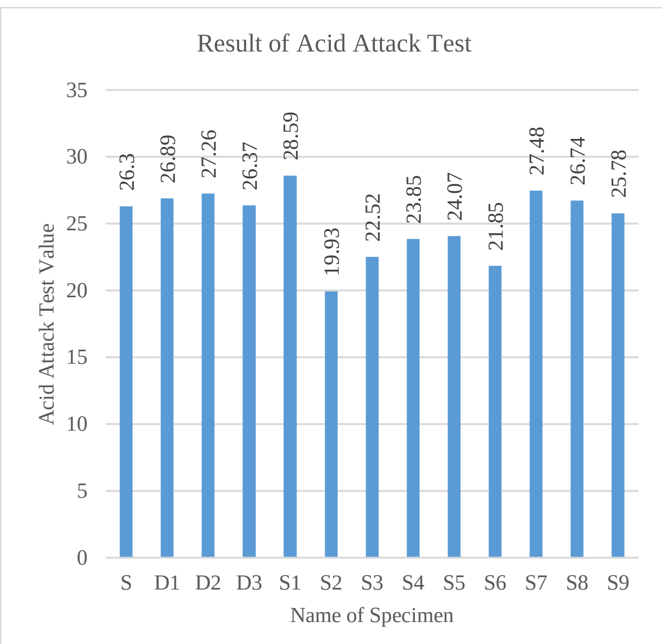

Fig. 10 Graph of the result of acid attack durability observation

7.5.2. Sulphate Attack Durability Observation

Table 11. Sulphate attack durability observation

Sr. no.	Name of Specimen	No. of Cube			Compressive strength after 56 days in N/mm2
		1	*2*	*3*	
1	S	23.56	24.44	26.22	24.74
2	D1	28.89	27.56	26.22	27.56
3	D2	23.78	26.00	24.44	24.74
4	D3	28.89	25.33	26.22	26.81
5	S1	24.89	26.89	25.78	25.85
6	S2	25.33	24.44	26.44	25.41
7	S3	23.11	21.33	22.44	22.30
8	S4	28.00	28.89	26.22	27.70
9	S5	23.56	25.78	25.11	24.81
10	S6	28.00	25.33	26.89	26.74
11	S7	24.89	28.22	27.33	26.81
12	S8	24.44	26.44	24.67	25.19
13	S9	25.78	27.56	26.44	26.59

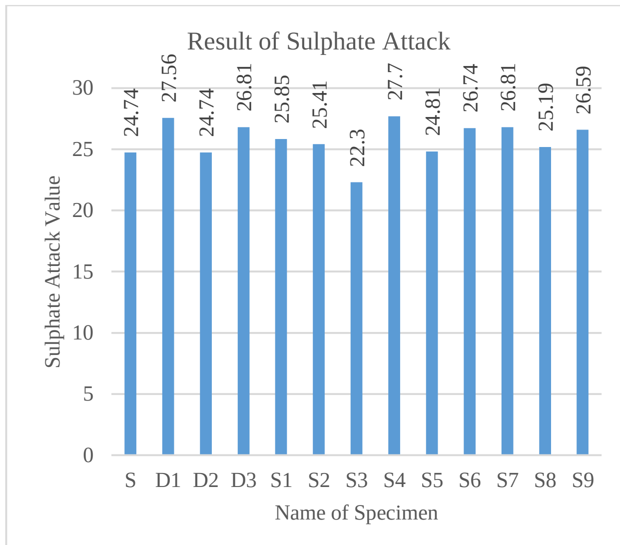

Fig. 11 Graph of the result of sulphate attack durability observation

7.6. Comparative Analysis

The results of this current study are similar to the results of Kaufmann [3], who observed that desert sand concretes improved mechanical stability when fine particles were effectively distributed in the concrete matrix, and Park et al. [23], who determined that the incorporation of metakaolin enhanced chemical resistance in blended cement systems. The comparative characteristics suggest that the thought-out dual replacement of desert sand and metakaolin provides a dual advantage — improving mechanical properties and resistance to chemical attack — without losing overall strength. This demonstrates the capability of desert sand-metakaolin composites as a green solution for long-lasting construction in potentially aggressive environments with an arid climate.

7.6.1. Comparative Analysis of Compressive Strength and Acid Attack Test

Figure 12 shows you a comparison of the compressive strength and acid resistance for traditional cements with Metakaolin (MK) and Desert Sand (DS) blended cements. Moderate replacement levels showed improvements in strength through enhanced particle packing and pozzolanic activity of the metakaolin.

The S5 mix (20% DS + 10% MK) had the increased compressive strength and the least amount of strength loss from the acid exposure.

The denser microstructure must come from the additional CSH gel generated in the mix, which refines pore structure and prohibits acid from reaching samples, thus improving durability and long-term performance.

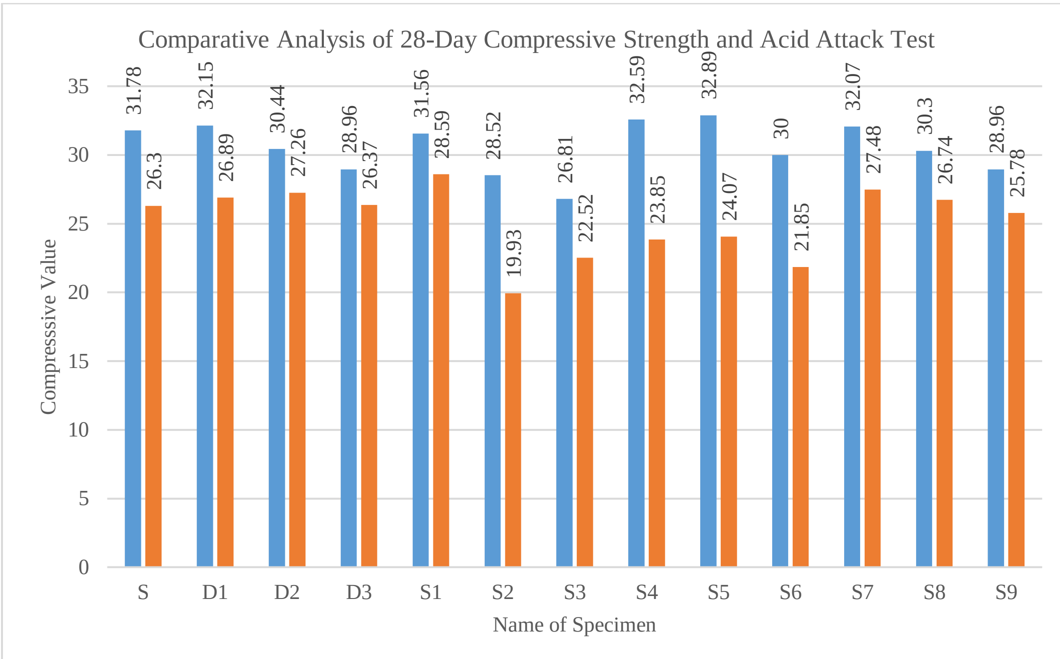

Fig. 12 Graph of comparative analysis of 28-day compressive strength and acid attack test

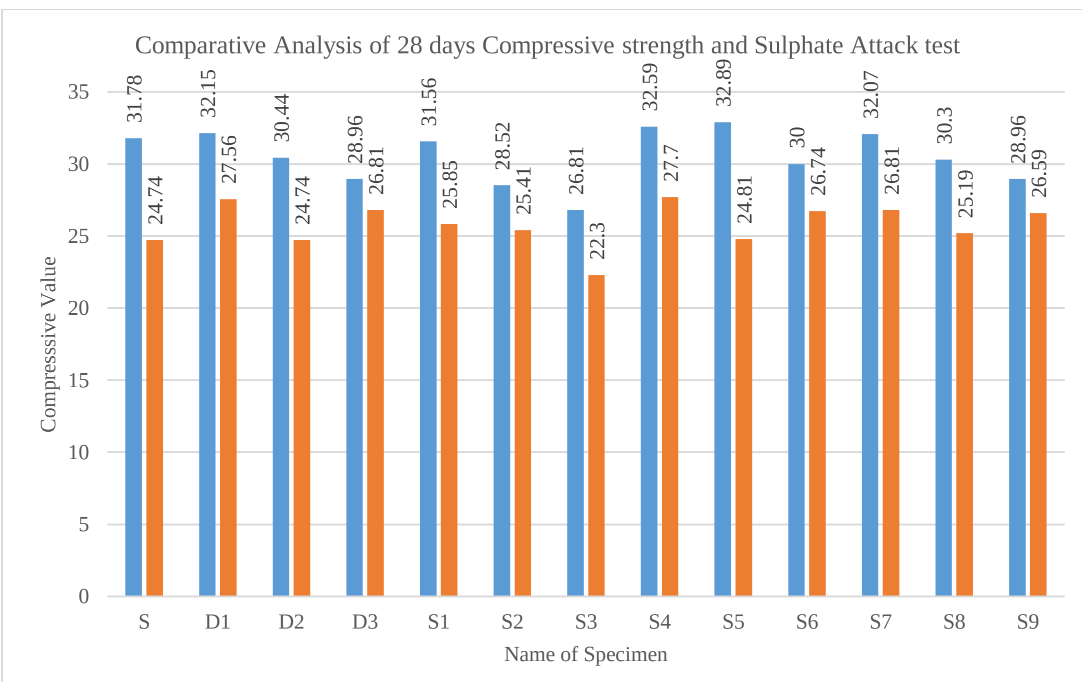

Fig. 13 Graph of comparative analysis of 28-day compressive strength and sulphate attack test

7.6.2. Comparative Analysis of 28-day Compressive Strength and Sulphate Attack Test

In Figure 13, the sulphate resistance of the mixes is shown, with the S5 mix again showing the best performance, where the mix retained 91% of its strength after 28 days of exposure to sulphate. The combination of DS and MK limited the formation of expansive compounds such as ettringite and gypsum to avoid deterioration of the surface. The mixes with the greatest DS or MK showed some loss in performance, but only by a slight margin, as the increased porosity led to a small reduction in the comparison of the sulphate exposure. As noted by Kaufmann [3] and Park et al. [23], replacing portions of the cement with both DS and MK resulted in better mechanical and chemical durability to make the mixes appropriate for a situation of construction with intended durability in a highly aggressive environment.

8. Conclusion

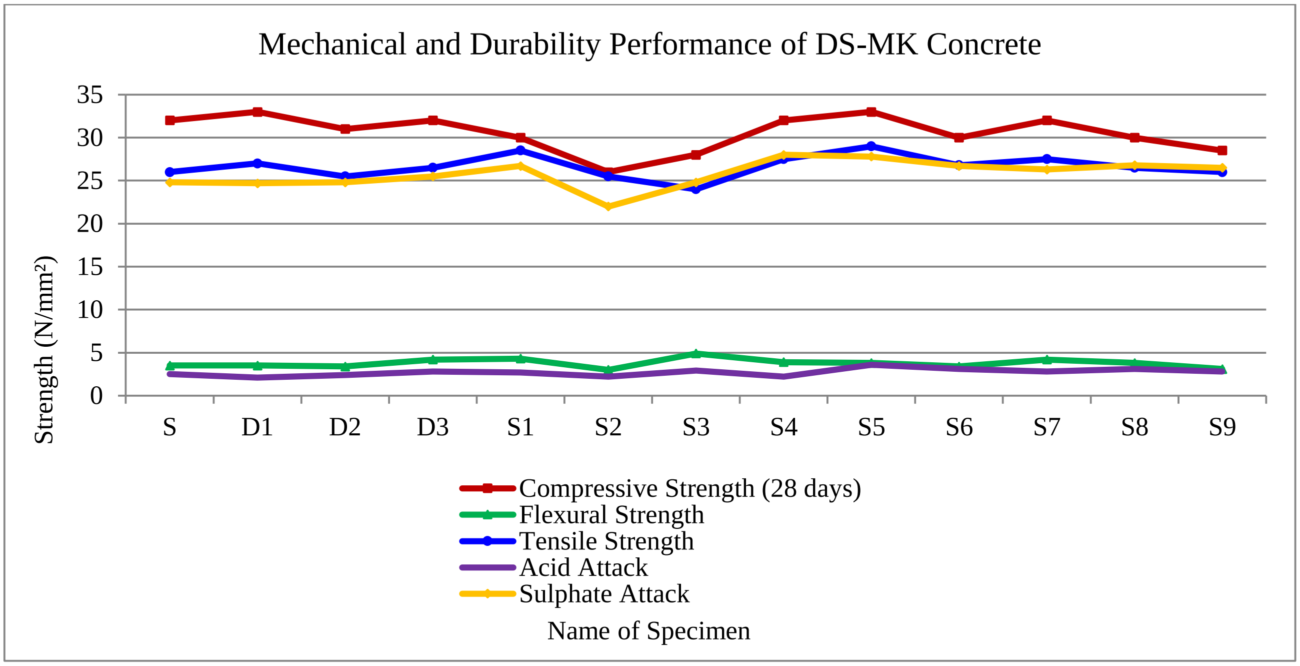

Fig. 14 Mechanical and durability performance of DS–MK concrete (compressive, flexural, tensile, acid, and sulphate strengths with values)

From the findings and discussion above, the following conclusions can be made:

- The application of desert sand (up to 20%) as a partial replacement improves workability and compactness of concrete due to its finer particle size and packing density.
- Using metakaolin (5% to 15%) as a partial substitute of cement improves compressive, flexural, and tensile strength due to its pozzolanic reaction and pore refinement.
- The optimum mix was 20% DS and 10% MK (Specimen S5). This combination had the compressive strength highest 28-day (32.89 MPa) and also showed increased resistance to acid and sulphate attacks.
- Results from the durability tests showed that DS–MK concrete had less strength loss when exposed to harsh chemicals, making it more applicable to coastal and industrial environments.
- The synergistic effect of desert sand and metakaolin occurs due to microfilling and pozzolanic action, as discussed in the work of Zareei et al. [20] and Kannan and Ganesan [13]. Conclusively, overall, it can be said that S5 will provide better results when compared to conventional concrete.

8.1. Practical Implications

The results presented here show that desert sand and metakaolin can be successfully used to create sustainable and durable concrete products that are especially useful in arid regions reporting a lack of natural sand. The optimized mix (20% DS + 10% MK) can achieve less environmental impact and reduce costs, all while maintaining full functionality of the concrete structure.

8.2. Future Scope

To enhance the possibility of this research, the following future possibilities are suggested:

- Microstructural assessment using SEM, XRD, and FTIR for the evaluation of hydration products and pore structure characterization.
- Long-term durability through carbonation, chloride penetration, and freeze–thaw resistance evaluated in field situations.

- High-performance concrete with DS–MK combinations, both in self-compacting and high-strength concrete situations.
- Numerical modelling through statistical optimization (e.g., Response Surface Methodology) to extrapolate mechanistic performance trends.
- Environmental impact evaluation through life-cycle and cost-benefit analyses to verify sustainability benefits.

To sum up, the research undertaking offers a framework to formulate coefficient, durable, and regional adaptive concrete employing desert sand and metakaolin.

Acknowledgments

The authors are pleased to inform that the Research and Development Cell and Concrete Technology Laboratory of Dr.Subhash University have continued to support them throughout the study period the benefit of valuable resources. The Department of Civil Engineering has a lot of thanks for the responsible professors who offered training programs in addition to the technical assistance team and laboratory personnel, who offered assistant input with technical efficiency. We describe their deepest gratitude for their collaborative efforts and determination of the entire inspection team in the experimental and modeling phases.

References

[1] Fu Jia Luo et al., “Effect of Very Fine Particles on Workability and Strength of Concrete Made with Dune Sand,” *Construction and Building Materials*, vol. 47, pp. 131-137, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[2] Namitha Raveendran, and Vasugi Krishnan, “Engineering Performance and Environmental Assessment of Sustainable Concrete Incorporating Nano Silica and Metakaolin as Cementitious Materials,” *Scientific Reports*, vol. 15, no. 1, pp. 1-24, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[3] Josef Kaufmann, “Evaluation of the Combination of Desert Sand and Calcium Sulfoaluminate Cement for the Production of Concrete,” *Construction and Building Materials*, vol. 243, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[4] P. Dinakar, and S.N. Manu, “Concrete Mix Design for High-Strength Self-Compacting Concrete Using Metakaolin,” *Materials and Design*, vol. 60, pp. 661-668, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[5] Badrinarayan Rath et al., “Sustainable LC3 Concrete in the Circular Economy: Assessment of Mechanical, Microstructural, and Durability Characteristics with Surkhi, Metakaolin, Nano-Silica, and M-Sand Blended Concrete,” *Global Challenges*, vol. 9, no. 5, pp. 1-12, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[6] Ashwini Manjunath B T et al., “Partial Replacement of Sea and Desert Sand in Place of River Sand for Mortar in Construction,” *GRD Journals- Global Research and Development Journal for Engineering*, vol. 2, no. 7, pp. 81-85, 2017. [Google Scholar]

[7] G. Dhinakaran, S. Thilgavathi, and J. Venkataramana, “Compressive Strength and Chloride Resistance of Metakaolin Concrete,” *KSCE Journal of Civil Engineering*, vol. 16, no. 7, pp. 1209-1217, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[8] Fu Jia Luo et al., “Effect of Very Fine Particles on Workability and Strength of Concrete Made with Dune Sand,” *Construction and Building Materials*, vol. 47, pp. 131-137, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[9] Namitha Raveendran, and Vasugi Krishnan, “Engineering Performance and Environmental Assessment of Sustainable Concrete Incorporating Nano Silica and Metakaolin as Cementitious Materials,” *Scientific Reports*, vol. 15, no. 1, pp. 1-24, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[10] Josef Kaufmann, “Evaluation of the Combination of Desert Sand and Calcium Sulfoaluminate Cement for the Production of Concrete,” *Construction and Building Materials*, vol. 243, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[11] P. Dinakar, and S.N. Manu, “Concrete Mix Design for High Strength Self-Compacting Concrete Using Metakaolin,” *Materials and Design*, vol. 60, pp. 661-668, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[12] B. Rath et al., “Sustainable LC3 Concrete in the Circular Economy: Assessment of Mechanical, Microstructural, and Durability Characteristics with Surkhi, Metakaolin, Nano-Silica, and M-Sand Blended Concrete,” *Global Challenges*, vol. 9, no. 5, pp. 1-12, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[13] Kamel Hebbache et al., “Integrated Techno-Environmental Analysis of Finely Ground Silica Sand in Sustainable Mortar Production,” *Buildings*, vol. 14, no. 10, pp. 1-19, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[14] Yuqi Zhou, and Weiwei Liu, “Application of Granulated Copper Slag in Massive Concrete Under Saline Soil Environment,” *Construction and Building Materials*, vol. 266, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[15] Guoxue Zhang et al., “Performance of Mortar and Concrete Made with a Fine Aggregate of Desert Sand,” *Building and Environment*, vol. 41, no. 11, pp. 1478-1481, 2006. [CrossRef] [Google Scholar] [Publisher Link]

[16] A.S. Al-Harthy et al., “The Properties of Concrete Made with Fine Dune Sand,” *Construction and Building Materials*, vol. 21, no. 8, pp. 1803-1808, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[17] Songlin Zhang et al., “Experimental Study on Performance Influencing Factors and Reasonable Mixture Ratio of Desert Sand Ceramsite Lightweight Aggregate Concrete,” *Advances in Civil Engineering*, vol. 2020, no. 1, pp. 1-9, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[18] S. Elavarasan et al., “Experimental Study on Partial Replacement of Cement by Metakaolin and GGBS,” *Materials Today: Proceedings*, vol. 37, no. 2, pp. 3527-3530, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[19] Liao Taichang et al., “Effects of Desert Sand Substitution on Concrete Properties Using Desert Sand-Doped Artificial Sand As the Fine Aggregate,” *Ceramics - Silikaty*, vol. 66, no. 4, pp. 540-554, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[20] V. Kannan, and K. Ganesan, “Chloride and Chemical Resistance of Self Compacting Concrete Containing Rice Husk Ash and Metakaolin,” *Construction and Building Materials*, vol. 51, pp. 225-234, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[21] Q. Chen et al., “Comparative Studies of Dynamic Mechanical Properties of Desert Sand Concrete and Ordinary Concrete,” *Shock and Vibration*, vol. 2022, no. 1, pp. 1-13, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[22] Changwei Qu et al., “Mechanical Properties and Acoustic Emission Analysis of Desert Sand Concrete Reinforced with Steel Fiber,” *Scientific Reports*, vol. 12, no. 1, pp. 1-15, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[23] Nancy Kachouh, Hilal El-Hassan, and Tamer El-Maaddawy, “Effect of Steel Fibers on the Performance of Concrete Made with Recycled Concrete Aggregates and Dune Sand,” *Construction and Building Materials*, vol. 213, pp. 348-359, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[24] Ghida Alhakim, Oussama Baalbaki, and Lina Jaber, “Effects of Incorporation of Cement and Metakaolin on the Mechanical Properties of Poorly Graded Sand,” *Arabian Journal of Geosciences*, vol. 15, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[25] Josef Kaufmann, “Evaluation of the Combination of Desert Sand and Calcium Sulfoaluminate Cement for the Production of Concrete,” *Construction and Building Materials*, vol. 243, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[26] Christian Paglia, *Circularity of Cementitious Materials: A Practical Approach*, Cement and Concrete Research, vol. 160, 2022. [Google Scholar] [Publisher Link]