JOURNAL OF APPLIED ENGINEERING SCIENCES
ISSN: 2247-3769 / e-ISSN: 2284-7197

VOL. 15(28), ISSUE 2/2025
ART.NO. 465 pp. 293-302

FLEXURAL BEHAVIOUR OF RICE HUSK BIOCHAR AND METAKAOLIN MODIFIED CONCRETE BEAM

Beaula Jasmine Rajamohan[a]*, S.Venkateswaran[a], S.Vishnuvardhan[a]

[a] Department of Civil Engineering, Agni College of Technology, Thalambur, Chennai, 600130, India, E-mails:
*beaulagideon@gmail.com, venkatnathan36@gmail.com, vishnucool901@gmail.com

Received: 31.08.2025 / Accepted: 05.09.2025 / Revised: 20.10.2025 / Available online: 15.12.2025

DOI: 10.2478/jaes-2025-0035

KEY WORDS: Rice husk biochar, Metakaolin, mechanical properties, Flexural strength, synergetic effect.

ABSTRACT:

Although concrete is commonly utilized, it results in high CO_2 emissions from the production of cement and has limited durability in specific applications. In this context, this research examines the impact of partially replacing cement with rice husk biochar (RHB) and metakaolin (MK) both combined and individually on the mechanical properties and flexural behavior of reinforced concrete (RC) beams. The cement is replaced with 1% to 5% for RHB and MK and their mechanical properties and flexural behaviours were examined. The findings indicate that incorporating RHB beyond 1% resulted in decreased mechanical strength, while the combined replacement of 5% RHB and 5% MK (RBMC5) significantly improved concrete performance. The concrete mix containing 5% RHB and 5% MK exhibited a 15.5%, 15.4%, and 15.46% increase in compressive strength, split tensile strength and flexural strength as relative to Conventional concrete (CC), attributed to enhanced pozzolanic reactivity, pore refinement and interfacial bonding. Flexural tests on RC beams demonstrated that RBMC5 attained first crack, yield and ultimate loads that were 27.78%, 26.32% and 25.93% higher than the CC beam, along with enhanced ductility marked by increases in ultimate deflection and strain of 21.71% and 28.57%. The crack control was also enhanced, with a 13.10% reduction in maximum crack width, a 17.86% reduction in crack spacing, and a 50% increase in crack distribution. It was concluded that although RHB and MK showed specific advantages, their combined use as a replacement to cement resulted in the most significant enhancement in strength, deflection and cracking behavior.

1. INTRODUCTION

Ordinary Portland Cement (OPC) is an essential material in the construction sector because it has good workability, high compressive strength and durability properties. Its low cost of raw materials and well-established production methods make it suitable to both large and small-scale projects for making building components in form of mortar and concrete. It was reported that the global cement increase will be 12%-23% by 2050, driven by population growth, urbanization and infrastructure development worldwide (Cheng et al., 2023). The main components of the OPC primarily consist of limestone and clay, which hydraulically harden after being combusted at a temperature of about 1450°C and is then crushed into fine clinker. Currently, there is a lack of resources that are already an alarming issue in various regions globally. In addition, the process of cement manufacturing accounts for 5%-7% of total CO_2 emission, with estimates indicating that the production of one tonne of cement emits approximately 800 kg-1100 kg of CO_2 (Aslani et al., 2023). To tackle these issues, industrial and agricultural wastes have been used as cementitious material for cement in concrete production. Supplementary cementitious materials (SCMs), referred to as pozzolanic materials have demonstrated the ability to improve the characteristics of cementitious materials while decreasing construction cost (Fapohunda et al., 2017). Various SCMs, such as metakaolin, rice husk ash, limestone powder, silica fume, rice husk ash, fly ash and ground granulated blast furnace slag (GGBS) have been used to enhance the mechanical and durability properties of concrete (Raj et al., 2023). Recent development involves innovative approaches such as using biochar (BC), a carbon-rich product of thermochemical conversion of organic material in the absence of or limited presence of oxygen, as a possible medium of CO_2 capture and storage (Goel et al., 2021; Bhatia et al., 2021). BC is considered as one of the six most promising methods for carbon sequestration, since it has the ability to absorb more than 2 times of its own weight in CO_2 (Wang et al., 2021; Cuthbertson, 2019). Structures constructed with materials that include BC can serve as carbon sinks over the years, while steel or concrete does not aid in carbon capture (Senadheera et al., 2023). BC produced from biomass typically contains cellulose, hemicellulose, lignin and various organic compounds in different ratios, depending on the biomass feedstock utilized (Ma et al., 2019). These components exhibit porous structures. Researchers have been drawn to it because of its distinctive properties, including a high surface area, high porosity, functional groups, high cation exchange capacity, and stability, making it suitable for diverse applications. Recent studies have demonstrated that BC can be used as a supplementary cementitious material (SCM) in sustainable concrete production (Maljaee et al., 2021; Suarez-Riera et al., 2020; Wang et al., 2020; Danish et al. 2021; Maljaee et al., 2021). Sirico et al. (2020) found that incorporating 1% BC obtained from forest waste through gasification at 800 °C into the concrete can enhance its flexural strength, compressive strength, and fracture energy. Gupta et al. (2018a) reported that incorporating 15-20% of BC sourced from wood waste into cement mortar could decrease permeability and enhance the strength properties of the mortar. Ahmad et al. (2015) attempted to incorporate pyrolyzed bamboo at 850 °C into the cement paste at 0.05 wt.% to 0.20 wt.% in order to enhance the characteristics of the cement paste. They stated that incorporating 0.06 wt% of BC sourced from bamboo enhances the toughness and strength of cement paste by 103% and 66%. Gupta et al. (2018b) examined the impact of 1 wt.% to 2 wt.% BC obtained from food waste pyrolyzed at 500 °C on concrete properties and noted that adding 1 wt.% BC leads to a 35% and 40% decrease in sorptivity and water penetration. Additionally, they found that the addition of 1 wt.% BC results in a 20% increase in compressive and split tensile strength. Similarly, studies (Dixit et al., 2021; Song et al., 2023; Gupta & Kashani, 2021) indicated that adding 2 wt.% to 5 wt.% BC was optimal for higher compressive strength.

Approximately 750 million ton of rice is produced every year with a byproduct of 120 million tons of rice husk (Shukla, 2022). The byproduct is rice husk causes global warming and smog, which is also harmful to health. There is need to find a more appropriate way of utilizing this byproduct in a more sustainable way. To minimize the environmental effects of construction materials, the utilization of rice husk-derived BC has surfaced as a viable option. However, RHB was not fully explored in existing studies. Narmanova et al. (2024) indicated that BC from rice husks serves as a beneficial additive that enhances the mechanical properties of structural concrete, resulting in a 31.3% increase in the ultimate compressive strength of the concrete relative to the control concrete. Yang & Wang (2021) reported that inclusion of 5% rice husk-derived BC in concrete causes a 5.5% reduction in compressive strength at 28 days due to low oxide content along with high porosity of BC. Ghosal et al. (2022) reported that the compressive, tensile and flexural strength of rice husk-derived BC concrete at 1% replacement was increased by 1.89%, 2.85% and 7.34% as compared to control concrete. It was concluded that the compressive, tensile and flexural strength of concrete decreases beyond the 1% replacement level. Chen et al. (2022) concluded a high amount of RHB dosages can reduce the compressive strength of concrete. This reduction is explained by a high level of capillary pores and brittleness of BC. Similarly, Rashid et al. (2024) reported that increasing the RHB content decreased the flexural strength, which was attributed to porosity in BC that causes air to occupy the voids with stress concentrations in the tensile plane. Such results concur with the findings of Muthukrishnan et al. (2019), who reported that increasing the RHB content decreased the flexural strength 16%-27 %. Akram et al. (2024) conducted experimental investigations on the partial replacement of cement with RHB in concrete, at replacement levels ranging from 1% to 3.5%. The study reported that the compressive strength initially improved up to a 2% replacement level, beyond 2% causes a slight decrease in strength was observed. Similarly, Falliano et al. (2020) also reported that inclusion of BC beyond 2% causes a decrease in flexural strength.

Rice husk, a byproduct of rice production, poses significant environmental challenges such as global warming when improperly disposed, creating a need for sustainable utilization methods. RHB has gained attention as a potential additive in concrete, with studies reporting mixed results. While some researchers (Narmanova et al., 2024; Ghosal et al., 2022) have observed strength enhancement at low replacement levels, others (Yang & Wang, 2021; Chen et al., 2022; Rashid et al., 2024; Muthukrishnan et al., 2019) have documented strength reductions at higher dosages due to high porosity and brittleness. Akram et al. (2024) and Falliano et al. (2020) found optimum performance at 2% replacement level. However, existing research primarily focuses on the mechanical properties of RHB-modified concrete, with limited exploration of the flexural behavior of structural elements such as reinforced concrete (RC) beams incorporating RHB. Furthermore, the combined use of RHB with other supplementary cementitious materials like MK which may counteract BC's porosity issues, remains underexplored. Additionally, most studies assess narrow replacement ranges, often limited to 3.5% RHB, without systematically examining higher levels and their interaction with MK on structural performance. The proposed study addresses these gaps by investigating the flexural behavior of RC beams modified with varying proportions of RHB (0–5%) and MK (0–5%), both individually and in combination, to provide a comprehensive understanding of their effects on strength development and structural performance.

2. MATERIALS AND METHODOLOGY

2.1 Materials

2.1.1 OPC: The primary composition of the concrete mixes was the OPC 53 grade cement that was used in compliance with IS: 12269-1987. OPC is well-known for its consistency in quality and finds common uses in structural concrete due to its high early strength gain and fineness and adequate setting properties. To ensure conformance, the physical properties of the cement were measured and have been tested as per IS 4031. The specific gravity of 3.15, initial and final setting time of 30 minutes and 600 minutes and Blaine fineness of 300 m²/kg were found in compliance with the IS 4031. Table 1 shows the chemical composition of OPC determined using X-Ray Fluorescence (XRF) analysis.

Compounds	%
SiO_2	21.02
Al_2O_3	5.12
Fe_2O_3	5.69
MgO	1.22
CaO	60.84
K_2O	0.67
Na_2O	0.29

Table 1. Chemical composition of OPC

2.1.2 Biochar (BC): This study utilized BC derived from rice husk biomass subjected to limited oxygen conditions (controlled pyrolysis process), which was fired at a temperature of 600°C. This thermal process confirms that highly porous and carbon-rich material is produced that suits to be utilized in cement-based systems. After pyrolysis, the BC was cooled at ambient temperature in air and milled and sieved until fine powder with a particle size less than 75 µm was obtainable.

The BC enhances homogeneity of the cement mix due to its quality and penalizes conduciveness to potential pozzolanic activity by its raised reactive surface area. The BC was added, replacing OPC in 0%, 1%, 2%, 3%, 4% and 5% weight ratio of the cement. The physicochemical properties of the BC used were determined prior to adding it to the crop. It contained a high carbon (>70%), which is essential in carbon sequestration advantages and a pH of 9–10 that is favourable in ensuring that the cementitious environment is alkaline. The specific surface area of 350 m²/g was measured by the technique known as the BET (Brunauer–Emmett–Teller) method.

This high specific surface area helps in the internal curing, densification of microstructure and promote CO_2 adsorption during hydration. Table 2 shows the chemical composition of BC determined using X-Ray Fluorescence (XRF) analysis. The BC has the sulphur trioxide (SO_3) contents of less than 4% which is the upper limit value required to be used as a pozzolanic additive in cementitious matrix according to ASTM C618. The higher CO_2 concentration of 82.96% demonstrates that the pyrolysis process leads to carbon fixation within the structure of BC through decompaction of cellulosic matter and lignin.

Compounds	%
SiO_2	15.77
CO_2	82.96
Al_2O_3	0.03
Fe_2O_3	0.05
SO_3	0.08
MgO	0.04
CaO	0.19
K_2O	0.88

Table 2. Chemical composition of BC

The elemental composition of cement or SCMs offers essential insights regarding its chemical properties, structural stability and potential applications. CHNS elemental analysis is a conventional method employed to determine the proportion of carbon (C), hydrogen (H), nitrogen (N) and sulfur (S), whereas supplementary elemental evaluation detects associated inorganic elements like calcium (Ca), magnesium (Mg), silicon (Si) and iron (Fe). These elements collectively affect the surface chemistry, porosity, adsorption ability and reactivity of SCMs. Table 3 presents the elemental composition of BC as determined by CHNS analysis which found to have the highest percentage of elemental carbon of 41.01% present in their structure. In addition, the pozzolanicity of material depends on Si in the form of amorphous silica (SiO_2).

Compounds	%
C	41.01
H	2.12
N	0.68
Ca	0.13
Mg	0.11
Si	19.24
Fe	0.06

Table 3. Elemental composition of BC

2.1.3 Metakaolin (MK): Metakaolin is produced from kaolin clay, a fine white mineral historically used in porcelain production. Unlike industrial by-products or naturally occurring pozzolans, MK is specifically manufactured for cementitious applications. The production process involves controlled calcination and processing to refine its color, remove inert impurities and optimize particle size. These measures result in a product with high purity and significant pozzolanic reactivity, making it well-suited for use in concrete applications. The specific surface area of 15 m²/g. The chemical composition of MK determined using X-Ray Fluorescence (XRF) analysis was presented in Table 4.

Compounds	%
SiO_2	52.34
Al_2O_3	41
Fe_2O_3	1.9
SO_4	0.5
MgO	0.1
CaO	0.2
K_2O	0.75
Na_2O	0.21

Table 4. Chemical composition of MK

2.1.4 Fine aggregate: The locally sourced river sand was used as available fine aggregate that met IS 383:2016. It had well-graded sand that was clean and free of silt and organic materials. The specific gravity and the fineness of the fine aggregate were tested against IS: 2386 and found to be 2.56 and 2.75 respectively.

2.1.5 Coarse aggregate: The nominal maximum size of about 20mm coarse aggregate of crushed granite stone used conforms with IS 383-2016 standard. The specific gravity and absorption ratio of the coarse aggregate were calculated as per IS: 2386 and measured as 2.97 and 1.35 respectively.

2.1.6 Water: The potable water devoid of impurities and the presence of chlorides and sulphates was used for mixing of concrete. The pH of the water was measured as 6.5, as aligned with IS 456:2000 specification.

2.1.7 Steel bar: The reinforcement for the RC beam used was steel bars of Fe500 grade and diameter of 12mm, 10mm and 8mm. The ultimate tensile strength, yield strength and Young's modulus of the steel bar were obtained as 650 MPa, 500 MPa and 200 GPa respectively.

2.1.8 Superplasticizer: The BC usually increases the water requirement of the concrete mixture due to its high surface area and porous texture nature. This demand further may lead to reduction in slump and may cause segregation. The remedy of these issues can be resolved by the use of superplasticizer. The Polycarboxylate ether (PCE) based high-range water-reducing admixture was used to attain adequate workability. The amount of superplasticiser at which a desired slump of 100 mm was achieved and no segregation or bleeding occurred. The added superplasticizer was in the amount of 1% in terms of cement weight.

2.2 Methodology

The primary objective of this study is to investigate the flexural behaviour of RHB and MK modified concrete RC beams. The various test was planned and designed as per BIS, ASTM and ACI standards to achieve solutions for the objectives.

The concrete grade of M30 was designed as per IS: 10262-2019 guidelines The cement in the concrete mix was partially replaced with two supplementary cementitious materials (SCMs) such as RHB and MK at replacement levels of 0%, 1%, 2%, 3%, 4%, and 5%, both individually and in combination. Initially, the concrete mix was optimized with RHB and MK at replacement level of 0%, 1%, 2%, 3%, 4% and 5% through testing of its mechanical properties.

Then, the optimized replacement level of RHB and MK which gives high strength was used to cast the RC beam to examine its flexure behaviour. The mix proportion for the M30 grade concrete mix was included in Table 5.

Mix ID	Cement	RHB	MK	FA	CA	Water	SP
	(kg/m³)						
CC	400	—	—	680	1160	160	4
RBC1	396	4	—	680	1160	160	4
RBC2	392	8	—	680	1160	160	4
RBC3	388	12	—	680	1160	160	4
RBC4	384	16	—	680	1160	160	4
RBC5	380	20	—	680	1160	160	4
MKC1	396	—	4	680	1160	160	4
MKC2	392	—	8	680	1160	160	4
MKC3	388	—	12	680	1160	160	4
MKC4	384	—	16	680	1160	160	4
MKC5	380	—	20	680	1160	160	4
RBMC 1	396	2	2	680	1160	160	4
RBMC 2	392	4	4	680	1160	160	4
RBMC 3	388	6	6	680	1160	160	4
RBMC 5	384	8	8	680	1160	160	4
RBMC 5	380	10	10	680	1160	160	4

Table 5. Mix Compositions

2.3 Experimentation

2.3.1 Mix Proportioning and mixing: M30 grade concrete proportion with a target strength of 38.25 MPa as per IS: 10262-2009. The RHB, MK, aggregate, water and superplasticiser were measured as per its mix ratio and used it for mixing. Initially, the fine aggregate and coarse aggregate was added into the concrete mixer and mixed in a dry condition for around 2 minutes. Then, the cementitious material like cement, RHB and MK was added as per their respective proportions and mixed in a dry condition for further 2 minutes. Then the required amount of water-superplasticizer mixture was added into and further continuing the mixing to attain homogeneity.

2.3.2 Preparation of test specimens: Further, the fresh concrete mixture was filled into the cube mould of 150 mm for compressive testing, cylinder mould of 300 mm height with 200 mm diameter for split tensile testing and prism mould of 500 mm × 100 mm × 100 mm flexural strength testing. After 24 hours of moist curing, the specimens were demoulded from the mould and placed in a water tank for curing for various curing ages of 7, 14 and 28 days. As per IS: 516-2021, three specimens were cast for each concrete mix.

2.3.3 Preparation of RC beam: The fresh mixed concrete was poured into the steel beam mould sized 2500 mm x 250 mm x 150 mm and then adequately compacted with a needle vibrator. The beam was reinforced with two numbers of 10 mm diameter bars in the compression zone and two numbers of 12 mm diameter bars in the tension zone, designed according to IS: 456. Furthermore, 8 mm diameter stirrups are provided at 150 mm c/c spacing.

2.3.4 Tests on mechanical properties: The compressive strength, split tensile strength and flexural strength of different concrete samples were assessed at 7, 14 and 28 days of curing using cube, cylinder and prism specimens as shown in Figure 6, Figure 7 and Figure 8. The Universal Testing Machine (UTM) with a capacity of 1000 kN and a least count of 1 kN was utilized to perform these tests on the specimens as per the IS: 516-2021 standards. About 3 cube, cylinder and prism specimens were tested to determine the average compressive strength, split tensile strength and flexural strength of the concrete mix.

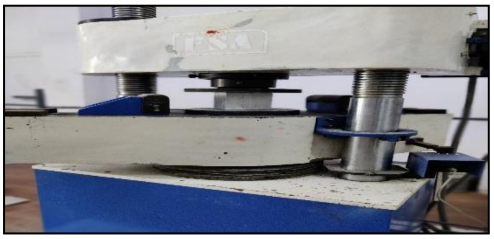

Figure 6. Compressive strength testing

Figure 7. Split tensile strength testing

Figure 8. Flexural strength testing

2.3.5 Tests on structural behaviour: After 28 days of curing, the beam was tested under two-point loading to assess its flexural behavior. Before testing, the beam was painted white, and a strain gauge was pasted on the front face of the beam to record the strain developed during loading as depicted in Figure 9. The beam was carefully positioned in the 40-ton capacity loading frame, and the required preparations were conducted to assess the different parameters. The LVDT was positioned at the mid-span of the beam to assess the deflection causes by an increase in load. The loading was applied incrementally; different parameters such as initial crack load, deformation, deflection and strain were observed. Additionally, the formation of a crack during loading was carefully marked with the marker. About 3 beam specimens were tested to investigate the flexural behaviour of the beam.

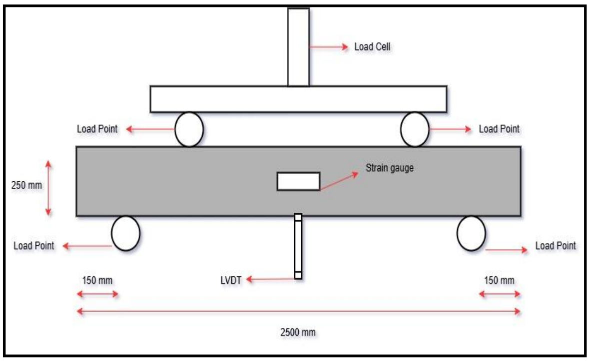

Figure 9. Test setup

3. RESULTS AND DISCUSSION

3.1 Compressive strength of RHB-MK Modified concrete

Table 10 presents the compressive strength of various concrete mixes modified with RHB and MK. The CC mix made with full (100%) cement as a binder attained the compressive strength of 38.25 MPa, which satisfies the minimum target strength for M30 grade concrete. The inclusion of RHB at a replacement level of 1%-5% decreases the compressive strength of concrete relative to CC mix as observed for RBC1-RBC5 mix. The highest compressive strength of 37.68 N/mm² was achieved for the RBC1 mix, which is about 1.49% less than the CC mix at 28 days. This reduction in compressive strength of RBC1-RBC5 mix in relation to CC mix can be due to a lower SiO_2 content of 15.77%. This lower reactive silica content limits its ability to actively participate in the pozzolanic reaction with $CaOH_2$, thereby reducing the formation of additional C-S-H gel that usually enhances strength. On the other hand, the inclusion of MK at a replacement level of 1%-5% increases the compressive strength of concrete relative to CC mix as observed for MKC1-MKC5 mix. The highest compressive strength of 42.08 N/mm² was achieved for the MKC5 mix, which is about 10% higher than the CC mix. This increase in compressive strength is due to the high reactive property of MK, when added into concrete as replacement to cement reacts with $Ca(OH)_2$ leads to formation of additional C-S-H gel, which is the primary contributor of concrete strength (Mohamed & Tayeh, 2024). This finding was consistent with existing studies (Dinakar et al., 2013; Weng et al., 2013; Zhang et al., 2021), which reported that inclusion of MK as a replacement for cement causes increases in compressive strength. Further, the combined addition of RHB and MK at replacement level of 1%-5% shows significant improvement in increases compressive strength as observed for RBMC1-RBMC5 mix. The combined addition of RHB and MK at replacement level of 1%-5% achieved the compressive strength of 38.44 MPa, 38.63 MPa, 38.82 MPa, 39.02 MPa and 44.18 MPa at 28 days. The highest compressive strength of 44.18 N/mm² was achieved for the RBMC5 mix, which is about 15.5% higher than the CC mix. The combined addition of RHB and MK to the concrete at a replacement level of 1% to 4% each show increase in compressive strength (38.44 MPa -39.02 MPa), which is only marginally higher than CC, which is due to the low reactive silica (15.77%) and porous nature of RHB, which was counterbalanced by the pozzolanic and filler effect of MK. At 5% replacement level, the effect became synergistic, in which MK rich in amorphous SiO_2 and Al_2O_3 (~93.34%), maximized its pozzolanic reaction and pore refinement, while the porous, CO_2-rich BC acted as a micro-reservoir for internal curing, sustaining later-age hydration and MK–CH reactions. This combination densified the paste and interfacial transition zone, enhanced mechanical interlock, and partially filled micro voids with carbonate precipitates, resulting in higher compressive strength.

Mix ID	Compressive strength (MPa)		
	7-day	14-day	28-day
CC	24.86	32.51	38.25
RBC1	24.49	32.02	37.68
RBC2	24.11	31.53	37.10
RBC3	23.74	31.05	36.53
RBC4	23.37	30.56	35.95
RBC5	23.00	30.07	35.38
MKC1	25.36	33.16	39.02
MKC2	25.85	33.81	39.78
MKC3	26.35	34.46	40.55
MKC4	26.85	35.11	41.31
MKC5	27.35	35.76	42.08
RBMC1	24.98	32.67	38.44
RBMC2	25.11	32.84	38.63
RBMC3	25.23	33.00	38.82
RBMC5	25.36	33.16	39.02
RBMC5	28.72	37.55	44.18

Table 10. Compressive strength of concrete

3.2 Split tensile strength of RHB-MK Modified concrete

Table 11 presents the split tensile strength of concrete modified with BC (RBC1- RBC5), MK (MKC1 - MKC1) and combined BC and MK (RBMC1- RBMC5). The inclusion of RHB at a replacement level of 1%-5% decreases the split tensile strength of concrete as relative to CC mix as observed for RBC1-RBC5 mix. The highest split tensile strength of 3.77 MPa was achieved for the RBC1 mix, which is about 1.57% less than the CC mix at 28 days. This reduction in split tensile strength is likely due to agglomeration, increased porosity, and higher water demand of RHB. Further, the high porosity of BC increases the water demand locally around particles, which can lead to micro voids and weaker interfacial transition zones (ITZ). On the other hand, the inclusion of MK at replacement level of 1%-5% increases the split tensile strength of concrete relative to CC mix as observed for MKC1-MKC5 mix. The highest split tensile strength of 4.21 MPa was obtained for MKC5 mix containing 5% MK, which is about 9.9% higher than the CC mix 28 days. Further, the combined addition of RHB and MK as a replacement for cement at 1%-5% shows a significant increase in split tensile strength in relative to CC mix as observed for RBMC1- RBMC5 mix. The highest split tensile strength of 4.42 MPa was obtained for RBMC5 mix containing 5% RHB and 5% MK, which is about 15.4% higher than the CC mix 28 days. The synergetic effect between the RHA and MK results in an increase of this split tensile strength. RHB, with its high surface area and porous structure, helps achieve micro filler and increase the mechanical interlock between the paste and aggregates while also providing internal curing by gradually releasing absorbed water, thereby promoting sustained hydration. Though RHB in its individual form contains low reactive silica (15.77%) and can dilute cementitious compounds, this is corrected by the fact that MK which is rich in reactive Silica (52.34%) and Al2O3 (41%) compensates through its strong pozzolanic activity to consume calcium hydroxide to form additional C-S-H and C-A-S-H gels. The resulting densification of the paste and interfacial transition zone reduces microcrack initiation and propagation under tensile loading, while the improved bond at the aggregate–paste interface increases tensile load transfer efficiency.

Mix ID	Split tensile strength (MPa)		
	7-day	14-day	28-day
CC	2.49	3.25	3.83
RBC1	2.45	3.20	3.77
RBC2	2.41	3.15	3.71
RBC3	2.37	3.11	3.65
RBC4	2.34	3.06	3.60
RBC5	2.30	3.01	3.54
MKC1	2.54	3.32	3.90
MKC2	2.59	3.38	3.98
MKC3	2.64	3.45	4.06
MKC4	2.69	3.51	4.16
MKC5	2.74	3.58	4.21
RBMC1	2.50	3.27	3.84
RBMC2	2.51	3.28	3.86
RBMC3	2.52	3.30	3.88
RBMC5	2.54	3.32	3.90
RBMC5	2.87	3.75	4.42

Table 11. Split tensile of concrete

3.3 Flexural strength of RHB-MK Modified concrete

Table 12 presents the flexural strength of concrete modified with BC (RBC1- RBC5), MK (MKC1 – MKC5) and combined BC and MK (RBMC1- RBMC5) at 7, 14 and 28 days. The CC mix achieved a flexural of 4.59 MPa at 28 days. The inclusion of RHB at replacement level of 1%-5% decreases the flexural strength of concrete as relative to CC mix as observed for RBC1-RBC5 mix. The highest flexural strength of 4.52 MPa was achieved for the RBC1 mix, which is about 1.52% less than the CC mix at 28 days. This reduction in flexural strength associated with high RHB level can lead to poor dispersion, agglomeration or increased porosity (Rashid et al., 2024; Muthukrishnan et al., 2019). The maximum reduction in flexural strength was observed for RBC5 mix. This flexural test results were found to be consistent with Tan et al. (2020), who reported that addition of BC causes a reduction in flexural strength by 20% at 28 days. Conversely, the inclusion of MK at replacement level of 1%-5% increases the flexural strength of concrete as relative to CC mix as observed for MKC1-MKC5 mix. The MKC5 mix with 5% MK achieved a maximum flexural strength of 5.05 MPa, approximately 10% higher than the CC mix after 28 days. Additionally, the combined addition of RHA and MK as replacement for cement at 1%-5% demonstrates a significant enhancement in flexural strength compared to the CC mix, as seen in RBMC1- RBMC5 mix. The maximum flexural strength of 5.30 MPa was achieved for the RBMC5 mix with 5% RHB and 5% MK, representing an increase of approximately 15.46% compared to the CC mix after 28 days. This improvement mainly results from the synergistic impact of high pozzolanic reactivity of MK and the ability of RHB to modify microstructure. MK, possessing a substantial level of amorphous SiO_2 (52.34%) and Al_2O_3 (41%), interacts with calcium hydroxide to produce additional C–S–H and C–A–S–H gels, which enhance the matrix density, refine the pores, and bolster the interfacial transition zone (ITZ). RHB, although it has a reduced reactive silica level (15.77%), acts as a micro filler and offers internal curing due to its porous, CO_2-enriched structure, promoting hydration at later stages and improving bond consistency. Under flexural loading, these influences are especially advantageous, as a denser paste and enhanced ITZ facilitate stress transfer, delay crack formation, and limit crack propagation.

Mix ID	Flexural strength (MPa)		
	7-day	14-day	28-day
CC	2.98	3.90	4.59
RBC1	2.94	3.84	4.52
RBC2	2.89	3.78	4.45
RBC3	2.85	3.73	4.38
RBC4	2.80	3.67	4.31
RBC5	2.76	3.61	4.25
MKC1	3.04	3.98	4.68
MKC2	3.10	4.06	4.77
MKC3	3.16	4.13	4.87
MKC4	3.22	4.21	4.96
MKC5	3.28	4.29	5.05
RBMC1	3.00	3.92	4.61
RBMC2	3.01	3.94	4.64
RBMC3	3.03	3.96	4.66
RBMC5	3.04	3.98	4.68
RBMC5	3.45	4.51	5.30

Table 12. Flexural strength of concrete

3.4 Flexural behaviour of RC beam

Figure 13 presents the load-deflection behaviour of the reinforced concrete beam modified with RHB and MK. During the initial loading phase, all beams exhibit a linear load-deflection behaviour until they reach a deflection of around 11.1 mm, which signifies the elastic stage where both the concrete and reinforcement work together to resist the applied load. The slope of the load-deflection curve in this region indicates the initial stiffness of the beams. The RBMC5 beam exhibits the highest stiffness followed by MKC5, RBC1 and CC beam. This indicates that inclusion of RHB, MK and their combination significantly improve the stiffness of the concrete beam. The synergetic effect in the RBMC5 beam likely promotes improved interfacial bonding and internal structure refinement, thus contributing to this improved deflection behaviour. The first crack load, marking the moment when the concrete in the tension zone begins to fail at 18 kN for CC, 20 kN for RBC1, 21 kN for MKC5 and 23 kN for RBMC5. This trend indicates that all concretes modified with additives exhibit superior resistance to cracking when compared to the conventional concrete (CC) mix beam. RHB, as a carbon-dense and porous substance, aids in enhancing the microstructure and resisting crack growth. Similarly, MK might aid in enhancing matrix densification. The synergistic combination in BAC3 exhibits the highest resistance to crack initiation, indicating that the RHB and MK collectively work together to improve tensile stress distribution and crack-bridging ability. The findings demonstrate the advantages of rice husk BC as compared to using rice husk ash as a partial replacement for cement in concrete. i.e., El-Sayed et al. (2019) reported that the RC beam containing 10% rice husk ash starts cracking at the load of 10 kN. However, the first crack load of RC beam containing 5%RHB and 5%MK start cracking at the load of 23 kN. The yield loads of the CC, RBC1, MKC5 and RBMC5 was are 38 kN, 42 kN, 44 kN and 48 kN. The findings show that the concrete matrix modified with RHB and MK not only postpones cracking but also improves the bond with steel reinforcement, enabling the beam to carry higher loads before yielding. Specifically, the RBMC5 beam demonstrates the highest enhancement in yield strength, indicating that the hybrid additives (RHB and MK) enhance load transfer, internal friction, and confinement effects in the concrete. After yielding, all beams enter a non-linear stage where stiffness decreases due to the cracking of concrete and yielding of reinforcement. Even with the softening behavior, the additive-modified beams still demonstrate increased load-bearing capability until failure. The CC beam eventually attains a maximum load of 54 kN, whereas RBC1, MKC5 and RBMC5 achieve 60 kN, 62 kN and 68 kN respectively. The RC beam containing 5%RHB and 5%MK has an ultimate load of 68 kN outperforming the RC beam containing 10% rick husk ash has an ultimate load of 63 kN as reported by El-Sayed et al. (2019). Similarly, the RC beam containing 5%RHB and 5%MK has an ultimate load of 68 kN outperforming the RC beam containing 10% rick husk ash has an ultimate load of 39.41 kN as reported by Chachar et al. (2022). Incorporating 5% MK with 5% RHB enhances particle packing, accelerates pozzolanic activity and refine pore structure, leading to a denser matrix and increased load-bearing capacity. The combination of reactivity and microstructural improvement accounts for the continual advantage of the 5% RHB + 5% MK mix compared to higher single RHB replacements. Moreover, the RBMC5 beam demonstrates the highest ultimate deflection of 18.5 mm, whereas the CC beam has a deflection of 15.2 mm. This indicates not only better strength but also increased ductility and energy absorption, which are essential for structural resilience. The increased deformation capacity of RBMC5 can be attributed to better microcrack control, aggregate bonding and stress distribution provided by the hybrid RHB-MK matrix. The results indicated that incorporating additives like RHB and MK, whether individually or together, positively influences the flexural performance of reinforced concrete beams. The RBMC5 beam found to be offer better flexural performance in terms of initial stiffness, cracking resistance, yield strength and ductility showcasing the benefits of using RHB and MK as partial replacement for cement. These findings indicate the feasibility of including bio-based and carbon-capturing materials in structural concrete to attain both improved performance and environmental sustainability.

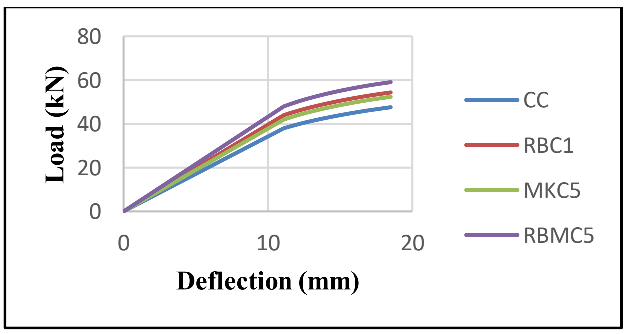

Figure 13. Load-deflection behaviour

Figure 14 presents the stress–strain behaviour of the beam such as CC, RBC1, MKC5 and RBMC5. The CC beam represents conventional concrete reinforced by steel, acting as the control specimen. The RBC1 beam contains 1% RHB based on the weight of cement, the MKC5 beam has 5% MK, while the RBMC5 beam presents a mix of 5% RHB and 5% MK. The stress–strain curves illustrate the transition from elastic to inelastic behavior, capturing both stiffness and ductility properties. In the initial elastic zone, extending to about 1.62 $\times10^{-3}$ strain, all beams demonstrate a linear increase in stress with strain, indicating the uncracked and reversible deformation phase. This phase is influenced by the elastic modulus of the composite material, with the load being distributed between the concrete and the reinforcement. The CC beam exhibits the lowest slope, signifying the lowest stiffness. In comparison, the RBC1 and MKC5 beams show significantly higher stiffness, which indicates the positive effect of the additives on the mechanical properties of the concrete. The RBMC5 beam, containing both RHB and MK, exhibits the steepest slope, indicating the highest stiffness. This enhancement results mainly from the combined effects of both additives, where RHB improves internal curing and matrix densification, while MK facilitates secondary pozzolanic reactions, producing more calcium silicate hydrate (C-S-H) gel (El-Diadamony et al., 2018). These modifications result in enhanced particle packing, decreased porosity and stronger internal bonding. When the strain reaches approximately 1.62 $\times10^{-3}$, all beams start to show deviation from linearity, signalling the beginning of inelastic response or yielding. This is a crucial point in the stress–strain curve where microcracks initiate and irreversible deformation begins. At this point, the yield stress of the CC, RBC1, MKC5 and RBMC5 beam was 18 MPa, 20 MPa, 21 MPa and 23 MPa. The increase in the yield strain of the RHB and MK modified concrete beam indicates their improved resistance to crack initiation and better stress transfer throughout the matrix. The RBMC5 beam exhibits superior bond development and crack resistance due to the combined action of the RHB and MK as compared CC, BC3 and AC3 beam. Beyond the yield point, curve enters into a non-linear region, extending up to the respective ultimate strain value of 2.1 $\times10^{-3}$ for CC, 2.4 $\times10^{-3}$ for RBC1, 2.5 $\times10^{-3}$ for MKC5 and 2.7 $\times10^{-3}$ for RBMC5 beam. In this region, the CC beam exhibits early softening and attains a peak stress of 25.26 MPa before failure. However, RBC1, MKC5 and RBMC5 beam exhibit better strain hardening behaviour with their stress value of 29.37 MPa, 28 MPa and 32.11 MPa. This indicates the better post-yield performance of RHB and MK modified concrete beam. The findings concluded that the addition of RHB and MK into concrete significantly improves both strength and ductility of the reinforced beam.

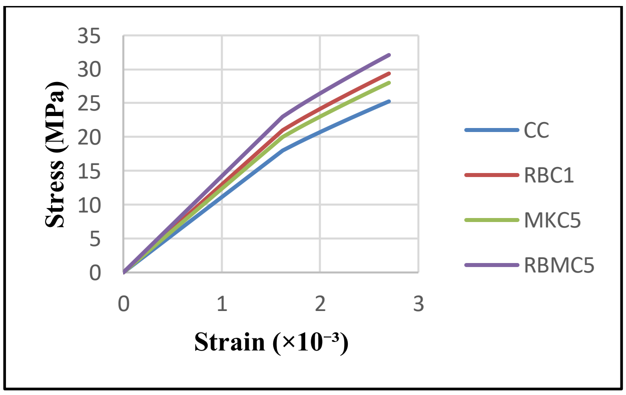

Figure 14. Stress–strain behaviour

The examination on the failure behaviour of the RHB and MK modified concrete beam showed a unique failure, which varied from brittle to ductile, as well as the variation of the crack width, the spacing of cracks and the crack number. The CC beam exhibits brittle flexure failure, which is a typical characteristic of conventional concrete with limited energy dissipation capacity. This failure mode is characterized by the sudden formation of a few wide cracks and sudden collapse immediately after the maximum load is reached. The maximum crack width of CC beam was 0.84 mm indicating poor crack control. It also has a maximum average crack spacing of 140 mm and developed only 12 cracks throughout its span. These indicate that the CC beam had poor tensile stress distribution and limited ability to redistribute internal stresses, leading to early crack localization and abrupt failure. On the other hand, the RBC1 beam with 1% RHB exhibited a ductile flexural failure. This behaviour is much more preferable than brittle failure since it involves gradual deformation and slower rate of load reduction and thus gives more warning to before collapse. The better crack control was observed in the RBC1 beam, which exhibits a narrower maximum crack width of 0.78 mm, average crack spacing of 125 mm and number of cracks of 15. These results indicate that the BC was beneficial in refining the pore structure, improved internal cohesion and increasing the stress bearing ability of the concrete in terms of pull or tension. As a result, the beam was able to develop more distributed and finer cracks, leading to absorbing more energy before failure. The MKC5 beam with 5% MK exhibited a shear-flexural failure pattern. This indicates that while the beam was able to withstand flexural stresses to some extent, it also shows signs of diagonal tension cracking, which is indicative of shear failure. The MKC5 beam possessed the maximum crack of 0.80 mm width, average spacing of 130 mm and a total number cracks of 14 cracks. This indicates a slightly moderate improvement as compared to CC beam and a slightly less effective than the RBC1 beam in crack controlling. This failure mode implies that the MK beneficial in improving the compressive strength through pozzolanic activity, may not significantly improve tensile ductility or shear resistance on its own. The most favourable failure performance was observed in RBMC5 beam that consists of 5% RHB and 5% MK. The RBMC5 beam possess a maximum crack width of 0.73 mm, minimum average crack spacing of 115 mm and the highest number of cracks of 18. The synergy between RHB and MK enhances both the physical matrix and chemical bonding, leading to improved microstructural properties, better reinforcement-matrix interaction and increased energy absorption capacity. The findings indicate that the incorporation of RHB and MK have a significant effect on the failure behaviour of reinforced concrete beams. Where the CC beam failed in a brittle manner with poor crack control, the RBC1 and the MKC5 beams demonstrated improved performance in terms of their increased ductility and better crack control. However, RBMC5 beam offers a better failure mechanism with the highest potential of ductility, cracking and dissipating energy. All findings are pointing to the fact that the hybridization of RHB and MK in the production of reinforced concrete structures would create a potential to achieve more durable, sustainable, and high-performance reinforced concrete structures.

The crack characteristics of the concrete beam such as CC, RBC1, MKC5 and RBMC5 provide significant insights into their structural integrity, serviceability and long-term durability. The parameters such as first crack load, maximum crack width, average crack spacing, and number of cracks are essential in evaluating the cracking behavior of concrete under flexural loading. The first crack load is that point when cracks can first be observed on the tension side of the beam, and this indicates the beginning of the post-uncracked elastic behaviour. The first crack load of the CC, RBC1 and MKC5 beam was 18 kN, 21 kN and 20 kN. This improved resistance to cracking in RBC1, MKC5 and RBMC5 beam is attributed to densification of the concrete matrix, better internal cohesion and stress distribution. However, the RBMC5 beam exhibits crack load of 23 kN, which is about 27.77%, 9.52% and 15% higher than the CC, RBC1 and MKC5 beam. The inclusion of RHB contributes in refining the pore structure and reducing micro-defects, while MK can improve the chemical bonding due to its pozzolanic properties. The combination of this mechanism in the RBMC5 beam is more effective to delay crack initiation than the RBC1 and MKC5 beam. The CC beam showed the widest cracks with a width of 0.84 mm and a reduction of the crack width was indicated by RBC1 and MKC5 beams with a width of 0.78 mm and 0.80 mm respectively. The narrowest cracks at 0.73 mm were found in the RBMC5 beam. Narrower crack width indicates improved crack control and better post-cracking behaviour, which is essential for preventing moisture ingress, minimizing reinforcement corrosion and ensuring structural longevity. This enhancement is attributed to the microstructural refinement and an enlarged tensile stress resistance imparted by the RHB and MK particles, particularly when used together. The average crack spacing is indicative of the uniformity of stress distribution and the ability of the concrete matrix to transfer loads across cracks. A lower crack spacing suggests more frequent but finer cracks, which is typically more favourable than fewer, wider cracks in regard to durability. The CC, RBC1 and MKC5 beam exhibited a highest crack spacing of 140 mm, 130 mm and 125 mm. The RBMC5 beam exhibits a uniform crack distribution with smallest average crack spacing of 115 mm. This denser cracking pattern is an indication of enhanced redistribution capacity of RBMC5 beam that is probably caused by a more homogenous internal matrix and better bond between the reinforcement and surrounding concrete. These findings are supported by the number of cracks that observed among the beams. The beam that had the least cracks was the CC beam with 12 cracks and the RBC1 and MKC5 had 15 and 14 cracks, whereas the maximum number of cracks of 18 was observed in the RBMC5 beam. The higher number of cracks with smaller width and closer spacing is an indication of a more ductile failure mode and better energy dissipation. Instead of stress concentrating and causing fewer and larger cracks, the RHB and MK modified concrete beam especially RBMC5 beam exhibit multiple finer cracks, which is a desirable behavior in reinforced concrete as it limits crack propagation and improves structural performance under load. Conclusively, it is quite evident that a RHB and MK-modified concrete beam cracks much better than the CC concrete beam. The RBC1 and MKC5 beams individually will demonstrate the increase in first crack load, crack control and crack spacing. However, under all parameters, RBMC5 beam shows the optimal performance in terms of highest first crack resistance, lowest crack width, densest crack spacing, and highest number of distributed cracks. Such improvements highlight the synergetic effect of a combination of RHB and MK and it results in excellent crack control and improvements in flexural performance. Table 15 presented the overall flexural parameters of RC beam

Parameter	CC	RBC1	MKC5	RBMC5
First Crack Load (kN)	18	21	20	23
Yield Load (kN)	38	44	42	48
Ultimate Load (kN)	54	62	60	68
Ultimate Deflection (mm)	15.2	17.6	16.9	18.5
Ultimate Strain ($\times 10^{-3}$)	2.1	2.5	2.4	2.7

Failure Behavior	Brittle flexural	Ductile flexural	Mixed shear-flexural	Ductile - flexural
Max Crack Width (mm)	0.84	0.78	0.80	0.73
Avg. Crack Spacing (mm)	140	125	130	115

Table 15. Flexural behaviour of RC beam

4. CONCLUSIONS

This study attempted to examine the effect of partial replacement of cement by RHB, MK both individually and in combination on the mechanical properties and flexural performance of the beam. It was observed that the partial replacement of cement by RHB and MK was 1% and 5%. The inclusion of RHB beyond 1% as a partial replacement for cement results in a decrease in the mechanical properties of the concrete. However, the combined inclusion of RHB and MK combination at 5% replacement level significantly enhances concrete strength and flexural performance of the beam. The RBMC5 mix exhibits a significant improvement in compressive strength, split tensile strength, flexural strength and bond strength. The compressive strength, split tensile strength, flexural strength of concrete modified with RHB and MK combination at 5% increases the compressive strength, split tensile strength and flexural strength by 15.5%, 15.4% and 15.46%. The improvement is attributed to RHB's pozzolanic activity, pore refinement, and improved interfacial bonding. The results indicate that the 3% optimum replacement level for obtaining better mechanical properties as compared to conventional concrete mix. Further, the RBMC5 beam containing 5% RHB and MK exhibits enhanced flexural performance as compared to the CC beam. The first crack load, yield load and ultimate load of the RBMC5 beam were 27.78%, 26.32% and 25.93% higher than the CC beam. Further, the ultimate deflection and strain were enhanced by 21.71% and 28.57% respectively, which means more ductility. The control of cracks also was enhanced and showed a reduced maximum crack width of 13.10%, spacing by 17.86% and a 50% increase of cracks. The findings concluded that although RBC1 and MKC5 had individual benefits, RBMC5 possesses significant improvement across strength, deformation and cracking behavior, confirming its potential as a sustainable concrete. This study focused only on the mechanical properties and flexural behaviour of RHB and MK-modified concrete. However, detailed microstructural investigations on this modified concrete were not considered and are recommended for future study.

References

Ahmad, S., Khushnood, R. A., Jagdale, P., Tulliani, J. M., Ferro, G. A. 2015. High performance self-consolidating cementitious composites by using micro carbonized bamboo particles. Materials & Design, 76, pp. 223-229.

Akram, M. U., Shahzad, M. K., Aslam, M., Jan, T. A., Sattar, T., Sibghatullah, H. M. 2024. Investigating the Effect of Rice Husk Biochar on Mechanical Properties and Chemical Resistance of Concrete. Southern Journal of Engineering & Technology, 1(1), pp. 216-229.

Aslani, A., Hachem-Vermette, C., Zahedi, R. 2023. Environmental impact assessment and potentials of material efficiency using by-products and waste materials. Construction and Building Materials, 378, p, 131197.

ASTM C618, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, https://store.astm.org/c0618-22.html

Bhatia, S. K., Palai, A. K., Kumar, A., Bhatia, R. K., Patel, A. K., Thakur, V. K., Yang, Y. H. 2021. Trends in renewable energy production employing biomass-based biochar. Bioresource Technology, 340, p.125644.

Chachar, Z. A., Ali, I., Raza, M. S., Das Narwani, T., Raza, I., Hussain, M. 2022. Flexural behavior of reinforced concrete beams by using rice husk ash as partial replacement of fine aggregates in cement concrete. J. Kejuruter, 34, p. 599-604.

Chen, L., Wang, L., Zhang, Y., Ruan, S., Mechtcherine, V., & Tsang, D. C. 2022. Roles of biochar in cement-based stabilization/solidification of municipal solid waste incineration fly ash. Chemical Engineering Journal, 430, p. 132972.

Cheng, D., Reiner, D. M., Yang, F., Cui, C., Meng, J., Shan, Y., Guan, D. 2023. Projecting future carbon emissions from cement production in developing countries. Nature Communications, 14(1), p. 8213.

Cuthbertson, D., Berardi, U., Briens, C., Berruti, F. 2019. Biochar from residual biomass as a concrete filler for improved thermal and acoustic properties. Biomass and bioenergy, 120, pp. 77-83.

Danish, A., Mosaberpanah, M. A., Salim, M. U., Ahmad, N., Ahmad, F., Ahmad, A. 2021. Reusing biochar as a filler or cement replacement material in cementitious composites: a review. Construction and building materials, 300, p. 124295.

Dinakar, P., Sahoo, P. K., Sriram, G. 2013. Effect of metakaolin content on the properties of high strength concrete. International Journal of Concrete Structures and Materials, 7(3), pp. 215-223.

Dixit, A., Verma, A., Dai Pang, S. 2021. Dual waste utilization in ultra-high performance concrete using biochar and marine clay. Cement and Concrete Composites, 120, p. 104049.

El-Diadamony, H., Amer, A. A., Sokkary, T. M., El-Hoseny, S. 2018. Hydration and characteristics of metakaolin pozzolanic cement pastes. HBRC journal, 14(2), p. 150-158.

El-Sayed, T. A., Erfan, A. M., El-Naby, R. M. A. 2019. Flexural behavior of RC beams by using agricultural waste as a cement reinforcement materials. J. Eng. Res. Rep, 7(1), pp. 1-12.

Falliano, D., De Domenico, D., Sciarrone, A., Ricciardi, G., Restuccia, L., Ferro, G., Gugliandolo, E. 2020. Influence of biochar additions on the fracture behavior of foamed concrete. Fracture and Structural Integrity, 14(51), pp. 189-198.

Fapohunda, C., Akinbile, B., Shittu, A. 2017. Structure and properties of mortar and concrete with rice husk ash as partial replacement of ordinary Portland cement–A review. International Journal of Sustainable Built Environment, 6(2), pp. 675-692.

Ghosal, S., Pani, P. K., Pattanaik, R. R., Ghosal, M. K. 2022. Mechanical characterization of concrete with rice husk-based biochar as sustainable cementitious admixture. In Recent Advances in Mechanical Engineering, pp. 227-233.

Goel, C., Mohan, S., Dinesha, P. 2021. CO2 capture by adsorption on biomass-derived activated char: A review. Science of The Total Environment, 798, p. 149296.

Gupta, S., Kashani, A. 2021. Utilization of biochar from unwashed peanut shell in cementitious building materials–Effect on early age properties and environmental benefits. Fuel Processing Technology, 218, p. 106841.

Gupta, S., Kua, H. W., Dai Pang, S. 2018a. Biochar-mortar composite: Manufacturing, evaluation of physical properties and economic viability. Construction and Building Materials, 167, p. 874-889.

Gupta, S., Kua, H. W., Koh, H. J. 2018b. Application of biochar from food and wood waste as green admixture for cement mortar. Science of the total environment, 619, pp. 419-435.

IS 383-2016, Coarse and fine aggregate for concrete, https://archive.org/details/gov.in.is.383.2016

IS 4031, Method of Physical Tests for Hydraulic Cement, https://law.resource.org/pub/in/bis/S03/is.4031.1.1996.pdf

IS: 10262-2019, Concrete mix Proportioning- Guidelines, https://law.resource.org/pub/in/bis/S03/is.10262.2009.pdf

IS: 12269-1987, Ordinary Portland Cement, 53 Grade — Specification, https://law.resource.org/pub/in/bis/S03/is.12269.1987.pdf

IS: 2386, Methods of Test for Aggregates for Concrete, https://law.resource.org/pub/in/bis/S03/is.2386.1.1963.pdf

IS: 516-2021, Hardened concrete methods of test part 1 testing of strength of hardened concrete section 1 compressive, flexural and split tensile strength, https://archive.org/details/gov.in.is.516.1.1.2021

Ma, Z., Yang, Y., Wu, Y., Xu, J., Peng, H., Liu, X., Wang, S. 2019. In-depth comparison of the physicochemical characteristics of bio-char derived from biomass pseudo components: Hemicellulose, cellulose, and lignin. Journal of Analytical and Applied Pyrolysis, 140, pp. 195-204.

Maljaee, H., Madadi, R., Paiva, H., Tarelho, L., Ferreira, V. M. 2021. Incorporation of biochar in cementitious materials: A roadmap of biochar selection. Construction and Building Materials, 283, p. 122757.

Mohamed, A. M., Tayeh, B. A. 2024. Metakaolin in ultra-high-performance concrete: A critical review of its effectiveness as a green and sustainable admixture. Case Studies in Construction Materials, 21, p. e03967.

Muthukrishnan, S., Gupta, S., Kua, H. W. 2019. Application of rice husk biochar and thermally treated low silica rice husk ash to improve physical properties of cement mortar. Theoretical and applied fracture mechanics, 104, p. 102376.

Narmanova, R., Yespanova, I., Kanzhar, S., Yusupova, L., Abildaev, N. 2024. Effect of rice husk biochar additive on concrete properties. In AIP Conference Proceedings, 3243(1), p. 020055.

Raj, B., Simon, K. M., Baburajan, R. 2023. Effect of supplementary cementitious materials on properties of self-compacting concrete. In International Conference on Structural Engineering and Construction Management, pp. 1-12.

Rashid, S., Raghav, A., Goyal, A., AB, D. R., Singh, M. 2024. Biochar as a sustainable additive in cementitious composites: a comprehensive analysis of properties and environmental impact. Industrial Crops and Products, 209, p. 118044.

Senadheera, S. S., Gupta, S., Kua, H. W., Hou, D., Kim, S., Tsang, D. C., Ok, Y. S. 2023. Application of biochar in concrete–a review. Cement and Concrete Composites, 143, p. 105204.

Shukla, S. S., Chava, R., Appari, S., Kuncharam, B. V. R. 2022. Sustainable use of rice husk for the cleaner production of value-added products. Journal of Environmental Chemical Engineering, 10(1), p. 106899.

Sirico, A., Bernardi, P., Belletti, B., Malcevschi, A., Dalcanale, E., Domenichelli, I., Moretti, E. 2020. Mechanical characterization of cement-based materials containing biochar from gasification. Construction and Building Materials, 246, p.118490.

Song, N., Li, Z., Wang, S., Li, G. 2023. Biochar as internal curing material to prepare foamed concrete. Construction and Building Materials, 377, p. 131030.

Suarez-Riera, D., Restuccia, L., Ferro, G. A. 2020. The use of Biochar to reduce the carbon footprint of cement-based materials. Procedia Structural Integrity, 26, pp. 199-210.

Tan, K., Pang, X., Qin, Y., Wang, J. 2020. Properties of cement mortar containing pulverized biochar pyrolyzed at different temperatures. Construction and Building Materials, 263, p. 120616.

Wang, L., Chen, L., Poon, C. S., Wang, C. H., Ok, Y. S., Mechtcherine, V., Tsang, D. C. 2021. Roles of biochar and CO2 curing in sustainable magnesia cement-based composites. ACS Sustainable Chemistry & Engineering, 9(25), pp. 8603-8610.

Wang, L., Chen, L., Tsang, D. C., Guo, B., Yang, J., Shen, Z., Poon, C. S. 2020. Biochar as green additives in cement-based composites with carbon dioxide curing. Journal of Cleaner Production, 258, p. 120678.

Weng, T. L., Lin, W. T., Cheng, A. 2013. Effect of Metakaolin on strength and efflorescence quantity of cement-based composites. The Scientific World Journal, 2013(1), p. 606524.

Yang, X., Wang, X. Y. 2021. Hydration-strength-durability-workability of biochar-cement binary blends. Journal of Building Engineering, 42, p.103064.

Zhang, S., Zhou, Y., Sun, J., Han, F. 2021. Effect of ultrafine metakaolin on the properties of mortar and concrete. Crystals, 11(6), p. 665.