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Design of New Process to Utilize Stubble Char for Constraction of M25 Concrete

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Abstract: Considering the challenges posed by agricultural waste, specifically rice straw, this study focuses on implementing cost-effective and eco-friendly processes to transform rice straw waste intovaluable, high-demand materials (sodium carbonate and M-25 concrete). The analysis of rice straw reveals its primary composition of cellulose and sodium silicate, with a layered cellulose microstructure. To produce sodium carbonate, rice straw is subjected to incineration ina furnace, with the resulting effluent gas passing through aqueous NaOH to effectively capture CO_2 at room temperature and ambient pressure. Simultaneously, the ash generated from burning rice straw is employed as a pozzolanic material in the production of M25 grade concrete.Notably, the concrete containing 20% ash demonstrates an impressive compressive strength of 29.05 MPa after a 28-day curing period. These results are highly promising for the potentialutilization of agricultural waste in the production of soda and concrete.
Keywords: Rice straw; CO_2 capturing; Ash utilization; M25 concrete

1. Introduction

The agriculture sector is the pillar of several developing and developed countries because with the rise in population the demand for food and food products increases, which can be fulfilled by scientific and modern agriculture technology. However, agricultural farming practices result in the generation of waste after they are harvested. Because the agriculture work has been done on large scale and the waste generated from agriculture cannot be ignored and proper care needs to be taken for their disposal[1]. Globally 140 Gt (gigatonne) agriculture waste is generated yearly, and this large quantity of waste creates serious landfill problems and has an impact on health as they contain various chemicals, minute metal particles, pharmaceuticals, and pathogens. Agriculture waste such as rice straw, wheat straw, rice husk, sugar cane straw, wood straw, and corn cobs are generally burnt while their disposal[2,3]. Of several food items, rice (*Oryza sativa*) is an important food crop used in regular meals by millions of people around the world. The current demand for rice utilization is reasonably high due to the increase in world populations and industrial growth[4]. A major problem of rice production is associated with the generation of a huge quantity of rice straw as residue and approximately 1-1.5 kg of straw is generated for every 1 kg of rice production[5]. Most of the farmers burn these unused rice straws in the open paddy field to clean their land for the next crop, the burning of rice straws in the open atmosphere causes serious air pollution as effluents are harmful to human health due to the pollutant gas and the solid dust particles[6,7]. It has been reported that globally 600-800 Mt (Megatonne) of unutilized rice straw is generated yearly[8]. During the combustion of agricultural residues, a huge number of gaseous effluents (mainly CO_2) and ashes as a byproduct are generated. It was estimated that annually 379 Tg (terragram) of CO_2, and 120 MT (metrictonne) ash with various gaseous effluents have been released from crop residue burning[6]. Utilizing rice straw can be beneficial for various applications, including livestock feed, bioenergy, and soil improvement. However, several challenges can hinder its effective utilization like high silica content, which can make it less palatable and digestible for livestock. Basta *et al*.[9] studied the effects of rice straw pulping processes on cellulose nano-architecture and how they react to indigo dye. Low energy content which limits its use as a feedstock for bioenergy production and Slow decomposition. While there are obstacles to using rice straw effectively, with the right approaches, it can still be a valuable resource for agriculture, bioenergy, and other applications. Various scientific research works proves that application of rice straw ash in concrete is very much beneficial in the respect of ecologically, economically. Number industrial projects are going on with various agricultural ashes. Project based on “benefits of improved rice husk combustion, bangladesh” has been initiated in December 2003 to find alternative uses of rice husk ash (DFID Project No R7659 Knowledge and Research Programme NRI Project No B0117 NRI Report No 2764)[10].

In recent years, several research works have been carried out to develop suitable methods for CO_2 capture and utilization of agriculture by-products[11]. The three common methods for CO_2 capturing are (a) pre-combustion capture, (b) oxy-fuel process and (c) post-combustion capture. Post-combustion CO_2 capturing is a challenge compared to the other two methods because during the post-combustion process diluted carbon dioxide is generated[11]. In the physical-chemical adsorption process, the adsorbents are based on carbon[12], zeolite[13], metal-organic framework[14-16], alkali metal-carbonate[15], and amine[17,18] are generally used for CO_2 capture. There are also some chemical processes for CO_2 conversion into lime, salicylic acid and phenol[19-21].

The M-25 concrete has high demand in construction industries. Because of the scarcity of raw materials, building materials are becoming more and more expensive every day[22,23]. As a result, obtaining natural resources for construction materials is turning into a worldwide concern. These findings imply that additional scientific research is required to provide ecologically friendly and sustainable construction materials without compromising or losing building quality. By using agricultural wastes instead of typical building materials like cement, the construction sector lessens the environmental damage caused by waste disposal in landfills. These agricultural wastes are used as alternative building materials, supplemental cementitious materials (SCMs), and substitutes for reclaimed aggregate. Constructional industries are also facing significant challenges in the production of building materials such as Ordinary Portland cement (OPC) which is related to the harmful environmental impact during their production[24]. The production of OPC is a very intensive process both in terms of energy and raw materials. Worrell *et al*.[25] reported that about 5% of total global anthropogenic CO_2 emissions are generated from OPC production. Nowadays, researchers are working on agricultural waste that can be used as a possible supplementary cementitious material (SCM) in concrete for improving its mechanical properties[26,27]. Over the last few decades, numerous studies have reported the design of new supplementary cementing materials derived from agricultural waste and their use as pozzolanic materials; however, their application as building materials is still not explored efficiently[28-35]. Rice straw ash is a pozzolanic material meets ASTM class N, F, and C pozzolana minimum standards, making it appropriate for usage as a substitute for portland cement. Furthermore, rice straw ash (RSA) is a useful partial cement alternative. Rice straw is burned to produce ash, which is primarily composed of silica-rich residue after the organic matter is removed[36]. But such heat treatment of the silica in the straw causes structural changes that affect the ash's grinding and pozzolanic activity. The amorphous ash is far easier to crush than the crystalline ash, according to Nimityongskull and Daladar[37]. The methods for producing ash range from open-heap combustion to specifically engineered incinerators. Open-heap burning is linked to pozzolanas with a low reactivity index because of the strong temperature gradient that causes the creation of an enhanced crystalline siliceous framework[38]. The impact of rice straw ash in various concrete types, such as high-strength or self-compacting concrete has also been explored. Rukzon *et al*.[39] produced self-compacting concrete (SCC) by use of blend of Portland cement with rice husk-bark ash. Their study showed that the rice husk-bark ash is effective for producing SCC with 30% of rice husk-bark ash replacement level. On the other work, experimentally investigatethe rheological and mechanical properties of SCC produced with rice husk ash (RHA)[40]. The suitability of untreated rice husk ash as a supplementary to the OPC and fine aggregates (FA) in high strength SCC was also investigated in terms of mechanical properties as well as environmental impact assessments (EIA)[41]. Malhotra *et al*.[42] studied the performance and characteristics of fly-ash, silica fume and rice-husk ash in concrete. It has been reported that the addition of fly ash to cement increases the compressive, tensile, and durability qualities of the concrete. Rice husk and silica fume are great additives in concrete. The composition strength, however, is lower than that of conventional Portland cement concrete. Construction industry is actively exploring and implementing more sustainable practices and materials in concrete construction to reduce the environmental challenges. Researchers, industry professionals, and policymakers should collaborate to develop and promote innovative technologies, materials, and strategies that can significantly reduce the carbon footprint, energy use, and waste generation associated with concrete construction. As a result, novel materials such as rice straw ash and technologies have arisen with the goal of reducing the environmental imprint of concrete construction, improving its durability and performance, and contributing to the overall sustainability of the built environment.

The present work is focused on the conversion of gaseous and solid effluents of agricultural waste (rice straw) into useful materials, which has high demand in industry as well as environment friendly. To the best of our knowledge, this is the first compact roadmap to utilize rice straws and convert their effluents (solid and gas) into valuable products without negligible environmental pollution. The key idea behind this work is the proper management of agricultural waste without generating secondary waste along with the generation of valuable products which will be in high demand for regular use. For this purpose, we have burned rice straw in a furnace and allowed it to pass the gaseous effluents into an aqueous NaOH solution for complete CO_2 capture. The CO_2-captured NaOH solution has been used for making sodium carbonate which has high demand in the detergent industry and glass industry[43]. On the other hand, the rice straw ash generated after the burning of rice straw has been utilized as a pozzolanic material for the preparation of M25 grade concrete.

2. Experimental

2.1 Material and Method

Rice straw (collected from the agricultural farm near Mohali, India), NaOH (97%, CDH), Ordinary Portland Cement (OPC) and the furnace, sand, coarse aggregate (20 mm) and coarse aggregate (12.5 mm) were purchased from the local market of Mohali, India. All the chemicals were used as received without any further purification.

Fresh rice straw samples were cleaned thoroughly to remove soil contamination and then dried under the sunlight for one day. The rice straw (20 kg) was burned in a furnace. The evolved effluent gas (CO_2) during rice straw burning has been passed into the aqueous 1 M NaOH solution through a pipe. The obtained ash (4.2 kg) was used for the casting of M25 concrete preparation as described below. M25 grade concrete cubes were prepared according to IS 456-2000 standard. For the preparation of the design mix, rice straw ash, water and cement, coarse aggregate (20 mm) and coarse aggregate (12.5 mm) were mixed. During the casting of concrete, the water-to-cement ratio was kept 0.4-0.45 as per the standard[44]. As per IS 456-2000 plain and reinforced cement concrete code of practice, fly ash up to 35% can be used as part replacement of OPC in the concrete.

The composition of the design mix for the casting cube is given in **Table S1**. For this purpose, the cubic specimen of dimensions 150 mm × 150 mm × 150 mm was cast, and after demolding, the concrete was first dried in the air overnight followed by curing underwater for 7 days and 28 days. Before the cube casting, a slump cone test was also performed using a standard procedure[44]. Compressive strength values of cubic specimens were obtained usingauniversal testing machine according to IS standard 516-1959[43].

2.2 Material Characterization

Powder X-Ray diffraction (PXRD) studies were performed by Bruker D8Advance X-ray diffractometer of wavelength 1.54 Å, and Ni-filtered has been used to remove the Cu-$K_{\alpha 2}$ radiation. The step size and step time were kept at 0.001° and 1 s respectively. Fourier transform infrared spectroscopy (FTIR) was performed using Bruker in the wavenumber range 450 cm^{-1} to 4000 cm^{-1}. The surface area measurement has been done using nitrogen adsorption/desorption isotherms at 77 K using Quantachromeautosorb iQ2. The surface area was measured using the Brunauer-Emmett-Teller (BET) method. The sample has been degassed at 200℃ for 8 h before surface area measurement. Barrett-Joyner-Halenda (BJH) desorption isotherm has been used for the pore size distribution study. The surface morphology of the rice straw was investigated with scanning electron microscopy (JEOL, JSM-IT300) and elemental analysis studies were performed by Energy-dispersive X-ray spectroscopy (EDS, Bruker) attached with the scanning electron microscope. A transmission electron microscopy (TEM) study was carried out using JEOL JEM2100 at 200 kV acceleration voltage. For the preparation of TEM samples, the sample was dispersed in ethanol using an ultra-sonication process, and one drop of prepared dispersion was drop cast on a carbon-coated copper grid. Compressive strength measurement was conducted of each cubic concrete after completion of 7 days and 28 days of curing time. For this purpose, three concrete bricks were tested and the average compressive strength has been reported.

3. Result and Discussion

The present work is focused on the conversion of agricultural waste to useful and high-demand materials for our society and industry. To achieve this goal, the work has been carried out in three different stages. In the first stage, rice straw (agriculture waste) was burnt in the furnace and generated gas was passed through solvent for complete carbon capture. In the second stage, crystallization of the solvent (CO_2 captured solution) under controlled conditions to get solid mass has been attempted. Finally, M25 grade concrete cubes have been prepared using rice straw ash.

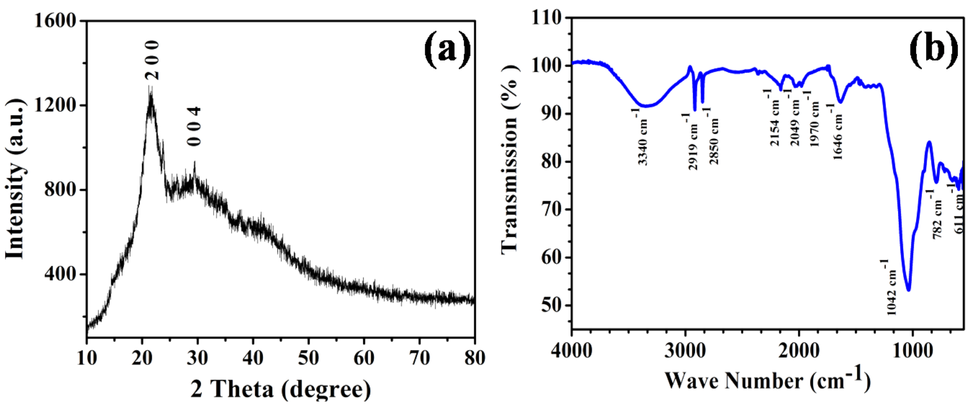

Figure 1. Characterization of dry rice straw (a) PXRD analysis; (b) FTIR spectra

Collected rice straw has been characterized via powder X-ray diffraction (PXRD). The PXRD of rice straw matched with a monoclinic lattice of cellulose(JCPDS card no. 00-060-1502) (**Figure 1a**). The rice straw contains high cellulose (30%-45%), hemicelluloses (20%-25%), lignin (15%-20%), silica and a small number of organic compounds such as protein present in it[44]. Further, FTIR spectra were recorded in 450 cm^{-1} to 4000 cm^{-1} (**Figure 1b**).

The FTIR spectra of rice show the presence of broadband at 3000-3500 cm^{-1}, which is associated with O–H stretching vibrations of hydroxyl groups and the intense peaks at 2910 cm^{-1} and 2850 cm^{-1} along with weak peaks at 2049 cm^{-1} and 1970 cm^{-1} were attributed to C–H stretching of CH_2 and CH_3 groups. In addition, a peak at 1646 cm^{-1} was usually assigned to the aromatic framework of the organic moiety. Absorption peaks at 1042 cm^{-1} and 782 cm^{-1} were assigned for Si–O–Si symmetric stretching of silica[45]. The observed FTIR bands of rice straw and rice straw ash have been summarized in **Table S2**. Elemental analysis of the dried straw has been carried out by energy-dispersive X-ray spectroscopy (EDS) (**Figure 2a**). It has been found that rice straw contains carbon (C), oxygen (O), and silicon (Si) as major constituents along with potassium. The rice plants utilized soil nutrients, water, and other minerals for their growth. The origin of silicon in the rice straw is from the soil because the soil contains silica. The morphology of rice straw was studied using SEM. SEM micrograph shows an organized and compact layered dent-like structural (microparticles of size 1-2 μm) features while preserving the typical composition of plant cell walls, including the epidermis, vascular bundles, and parenchyma attached to the bundle's surface (**Figure 2b and 2c**).

The rice straw can be utilized in several forms such as in energy, biofuel, biochar, and ash. The conversion of rice straw to these materials is generally done via thermal processes, where the decomposition of rice straw is exposed to heat ~300 ℃ [46]. The thermal conversion processes comprise pyrolysis, gasification, and direct combustion[46]. In this present study, we have designed a process for the combustion of rice straw where all the gasses and byproducts produced are efficiently converted into auseful product. After complete combustion of 20 kg of rice straws and 4.2 kg of ash were recovered from the furnace. It is also found that during the burning of rice straw, 11.4% of CO_2 was released from the reactor and ash has been collected from the bottom of the furnace.

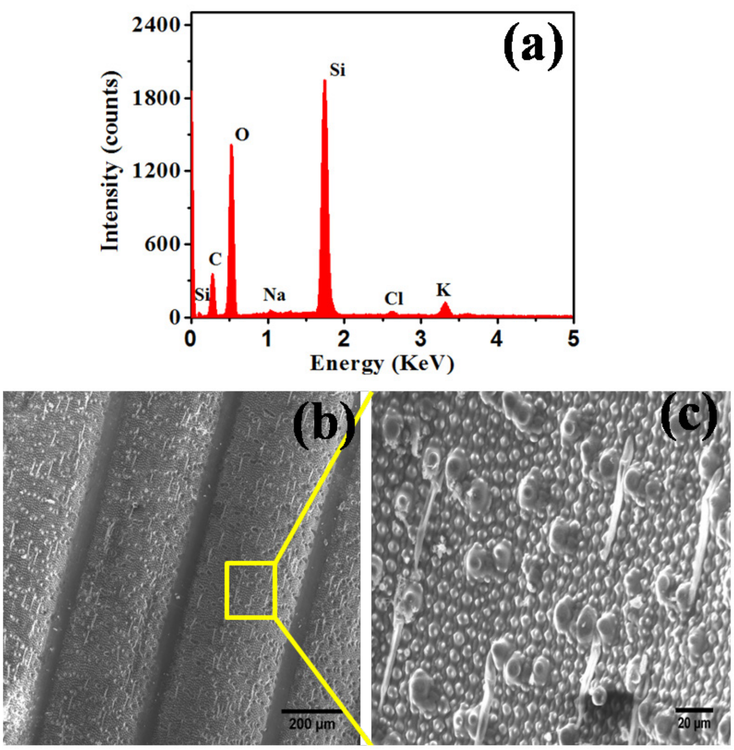

Figure 2. (a) EDS analysis, (b-c) SEM morphology of the dry rice straw

The gaseous effluent has been passed into a 1 M NaOH solution (pH 12.8) to capture the generated gas that arises during the burning of the rice straw and once the solvent pH reached 10.2, the flow of gas has been stopped. This CO_2-purged NaOH solution was then evaporated at ~ 100 C to get a solid product. The X-ray diffraction patterns of the solid product were matched with monoclinic sodium carbonate (Na_2CO_3; JCPDS PDF no 05-001-0022) (**Figure 3**). The seven highest diffraction peaks appear at 26.08°, 30.14°, 34.20, 35.25°, 37.51°, 38.01°, 39.97° corresponding to (111), (002), (020), (310), (021), (112), (202). The reaction for the formation of Na_2CO_3 involves four steps. In the first step, gaseous CO_2 was dissolved in an aqueous NaOH solution to form H_2CO_3.

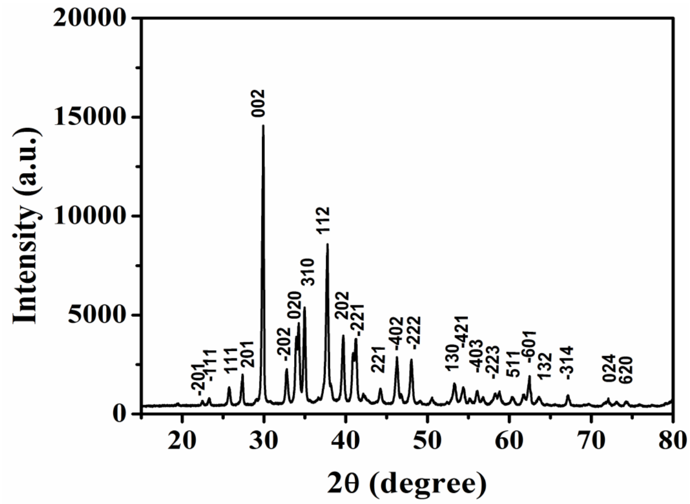

Figure 3. Powder X-ray diffraction patterns of sodium carbonate (Na_2CO_3)

In an aqueous solution H_2CO_3 is ionized into H^+, HCO_3^- and CO_3^{2-} and further reacts with Na^+ ion to form a sodium carbonate-bicarbonate solution. Further, heating of sodium carbonate-bicarbonate aqueous solution at 120℃ to get a solid product.

$$CO_2(g) \rightarrow CO_2(aq) \quad 1$$

$$CO_2(aq) + H_2O(l) \rightleftharpoons H_2CO_3(l) \rightleftharpoons H^+ + HCO_3^- \rightleftharpoons H^+ + CO_3^{2-} \quad 2$$

$$NaOH(s) \rightarrow NaOH(aq) \rightleftharpoons Na^+ + OH^- \quad 3$$

$$2Na^+ + CO_3^{2-} \rightleftharpoons Na_2CO_3(s) \quad 4$$

The overall reaction can be written in a simple form as;

$$2NaOH + CO_2 \rightleftharpoons Na_2CO_3 + H_2O \quad 5$$

Ash has been collected from the bottom of the reactor and characterized via PXRD, FTIR, EDS and TEM studies. The PXRD patterns of ash show the presence of the cubic sylvite phase of KCl. All the diffraction patterns (28.4, 40.3, 50.1, 58.3, 66.1) matched with JCPDS no. 00-041-1471 (**Figure 4a**). Apart from the above reflection pattern the broad peak in the range of 15-30, which corresponds to amorphous silica (SiO_2, PDF 01-083-2187). The functional group of rice straw ash has been evaluated by FTIR (**Figure 4b**). The intense IR band at 611, 782 cm^{-1} reveals the symmetric stretching of the Si–O bond. The presence of a band in rice straw ash at 1042 cm^{-1} corresponds to Si–O–Si asymmetric stretching. A peak at 1420 cm^{-1} is indicated the presence of a C=C aromatic skeleton in the ash. Additionally, two weak peaks at 2049 cm^{-1} and 1969 cm^{-1} were attributed due to the C–H stretching of CH_2 and CH_3 groups. The detailed FTIR analysis of the band is given in **Table S2**. BET analysis was attempted to understand the surface area of rice straw ash. The BET-specific surface area and the pore radii of ash were 176.5 m^2/g and 3.7 nm respectively (**Figure 4c and 4d**).

Microstructure analysis of ash has been performed using transmission electron microscopy (**Figure 5a**). TEM micrograph shows the ash nanoparticles of size 40-80 nm. The aggregated particles were attributed due to an effect of the combustion process. The elemental composition of ash has been analyzed by the TEM-EDX studies, which indicates the presence of silicon (Si), oxygen (O), carbon (C), chlorine

(Cl), phosphorous (P), potassium (K) sodium (Na), magnesium (Mg) (**Figure 5b**). Elemental analysis of ash shows that the sample contains a high amount of silica along with KCl. It is known that the high silica-contained rice straw ash would be a potential candidate for use as a pozzolan material for concrete preparation[47-49]. The presence of Na and Mg is due to the micronutrients of soil.

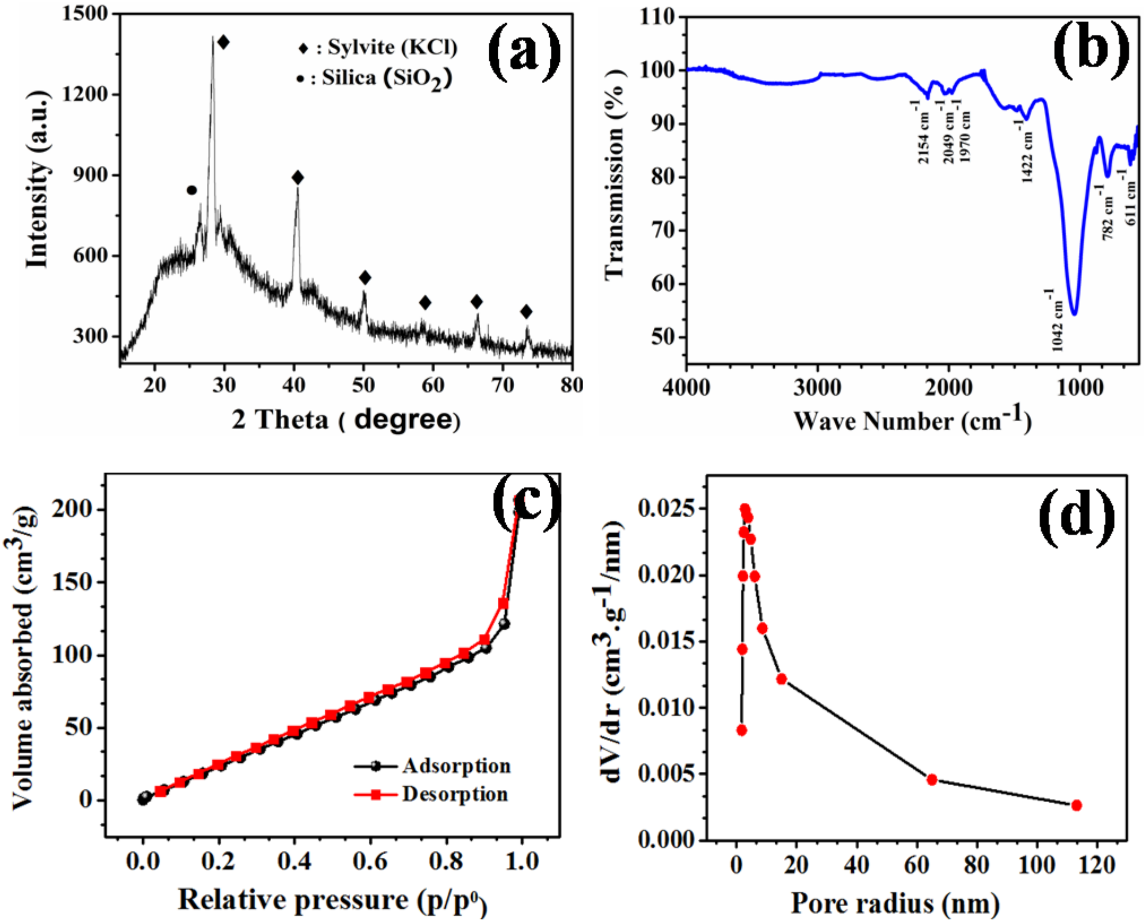

Figure 4. Characterization of rice stubble ash obtained after burning of rice straw (a) PXRD; (b) FTIR; (c) BET surface area and (d) pore size distribution

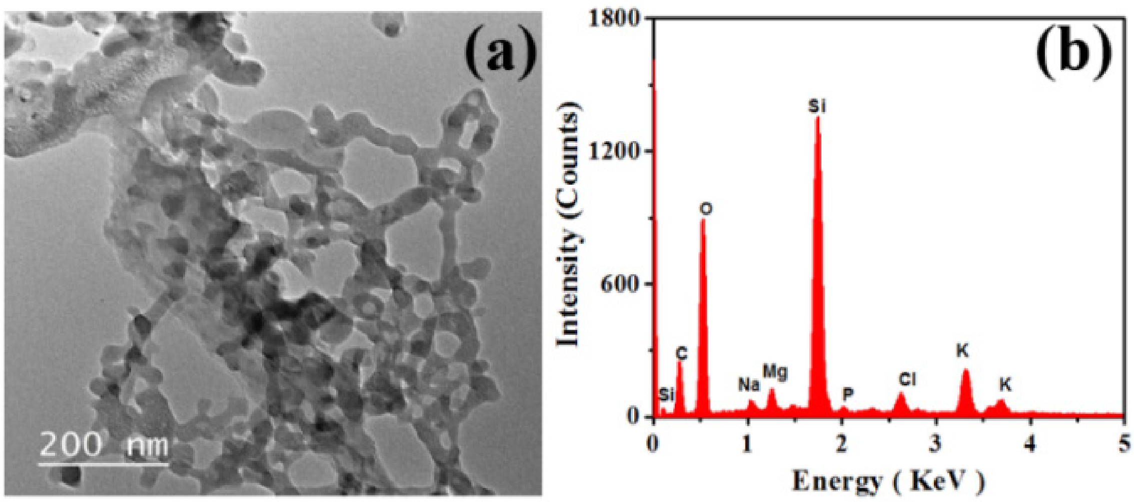

Figure 5. Morphological study of rice stubble ash (a) TEM; (b) EDX

The design mixture has been prepared according to IS 456:2000 standard. The PXRD of the OPC and sand is given in **Figure 6a and 6b** respectively. PXRD of the OPC shows that the OPC comprises the Gismondine ($CaAl_2Si_2O_8 \cdot 4H_2O$), Mullite ($Al_{4.8}Si_{1.2}O_{9.6}$) Brownmillerite ($Ca_2Al_2Fe_2O_5$) phases along with tricalcium silicate (C_3S: $3CaO \cdot SiO_2$) as a dominant phase.

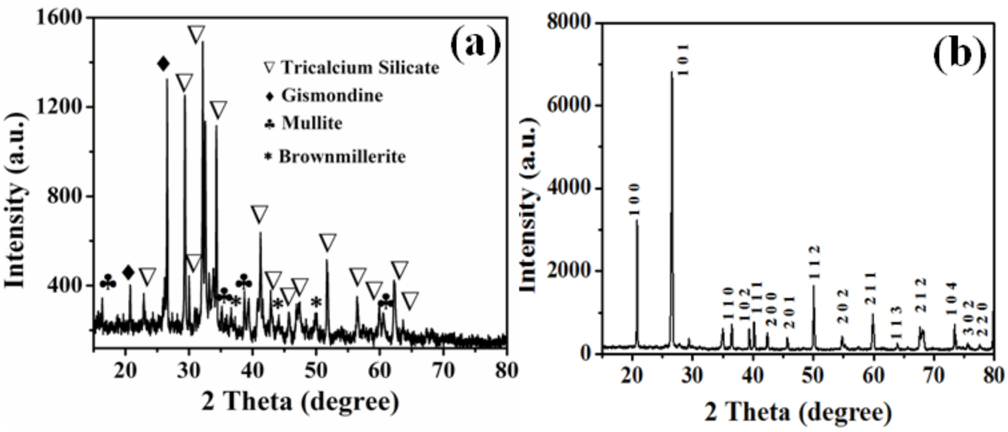

Figure 6. PXRD analysis of (a) Ordinary Portland cement, and (b) commercially available sand

PXRD study of the sand shows the hexagonal phase of silica (SiO_2, PDF 00-061-0035). In this study, the effect of Recycled and Secondary Aggregates (RSA, here ash) was studied for the preparation of M25 grade concrete and 20% of cement was replaced with RSA. A concrete slump test has been carried out to find out the workability of the design mix after the addition of RSA. The observed concrete slump value was 80 mm which signifies good workability of the design mix can be obtained when RSA is used along with a cement blender. The compressive strength of the concrete development at various curing ages (7 days and 28 days) is given in **Table 1**. The measured compressive strength of concrete after 7 days and 28 days was 20.75 MPa and 29.05 MPa respectively. **Figure 7** shows a comparative study of the compressive strength of the 20% ash-containing concrete with standard M25 concrete. The result indicates concrete with 20% RSA reached 88.01% strength after 7 days, and 116.21% strength after 28 days. Roselló *et al*.[33] reported a mortar with 25% rice straw ash reached 83.3% of the strength found for OPC control after 7 days and 98.4% after 28 days. Compressive strength of M25 concrete with various design mix has been given in **Figure S1**. From the study it has been found that when (Cement + RSA):Sand:total coarse aggregate ratio is 1:1.5:2.8 gives the better compressive strength with respect to other design mix.

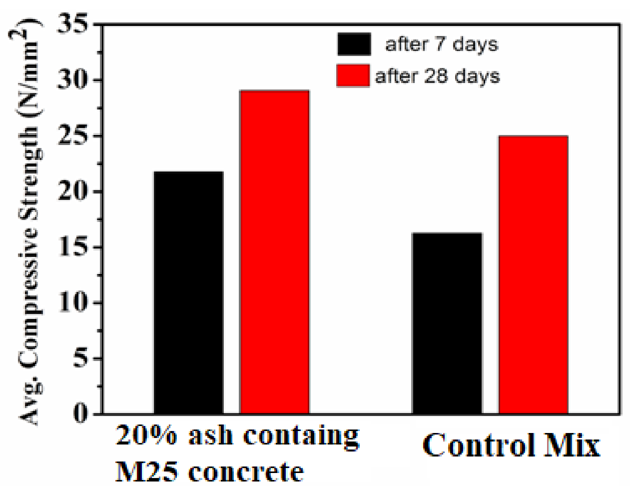

Figure 7. Compressive strength of M25 Concrete with 20% ash

Table 1. Weight and compressive strengths of 20% ash contain M25 concrete after 7 days and 28 days of curing

After 7 days				After 28 days			
Weight (kg)	Strength (N/mm^2)	Average strength (N/mm^2)	Strength with standard Deviation (N/mm^2)	Weight (kg)	Strength (N/mm^2)	Average strength (N/mm^2)	Strength with standard Deviation (N/mm^2)
7.970	21.78			8.000	29.87		
7.930	22.04	20.75	20.75 ± 0.30	8.150	28.96	29.05	29.05 ± 0.59
7.900	21.44			8.040	28.33		

In comprise, concrete prepared with 20% rice straw ash containing OPC gives enhanced compressive strength to the mortar with 25% rice straw ash. This enhancement of the compressive strength after the ageing of 7 days and 28 days is due to the improvement of alkali activation and pozzolanic reactivity of RSA as described earlier[33]. Pozzolans are important refractory materials containing fine particles of siliceous and aluminous materials which react with $Ca(OH)_2$ to form cementitious materials. Pozzolans are generally added to Portland cementing materials to improve cement quality. The reaction occurs due to the fine particle nature of silica nanoparticles. The BET analysis showed that the surface area and the pore radii of ash were 176.5 m^2/g and 3.7 nm respectively with the particle size size 40-80 nm (**Figure 5a**). This high surface area and nanosize ash particles helps in enhancing the strength of the concreate. Additionaly the strength of cement and ash mixture also improves because of the pozzolanic reaction between the silica and calcium hydroxide in aqueous media to form calcium silicate hydrate (Ca–Si–H). The reaction consists of the acid-base reaction between calcium hydroxide (produced during hydration of Portland cement) and silicon oxide (silica):

$$Ca(OH)_2 + SiO_2 \rightarrow Ca\text{–}Si\text{–}H\ (gel) \qquad 6$$

The chemical reaction produced calcium silicate hydrate gel (Ca–Si–H), which has enhanced cementing properties. This Ca–Si–H sets into the pores of the cement results in a reduced amount of pores which in turn decreases the permeability of the binder in the pores and their interaction with structural materials. The decrease in the permeability of binder in the pores diminishes its interaction with harmful ions such as chloride and carbonates, hence, giving better results over a long lifetime.Additionally, the amorphous silica presented in ash also help to enhance the cementing properties of rice straw ash.

4. Conclusion

In this present study, we have summarized the potential implications for complete CO_2 capture and ash utilization of the burnt rice straw to produce sodium carbonate (Na_2CO_3) and concrete from gaseous and solid wastes respectively. The CO_2 produced while burning rice straw was utilized for the synthesis of Na_2CO_3 which has a huge application in the glass industry and detergent industries. Solid effluent collects after the combustion process is tested from the reactivity point of view to evaluate for its utilization as a pozzolanic material. Physical characterization of rice straw ash has been done via PXRD, FTIR, EDS and TEM studies. TEM micrograph shows the ash nanoparticles of size 40-80 nm wherethe BET-specific surface area is 176.5 m^2/g. Compressive strength developed with 20% replacement by RSA offers 88.01% and 116.21% of the strength after 7 days and 28 days of curing, respectively, according to results from M25 grade concrete developed through mixing of RSA with OPC. This enhancement of compressive strength is due to the pozzolanic reactivity of the amorphous nature of the silica (SiO_2) present in the ash. These findings holds great promise for the sustainable reutilization of rice straw combustion byproduct in the production of soda and pozzolanic materials for concrete casting.

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Author’s Contributions

Methodology, investigation, validation, writing-original draft, writing-review and editing: Guchhait SK

Investigation, validation, writing-original draft: Ankush

Investigation, validation, writing-review & editing: Yadav KK and Sunaina
Helped in constraction of concrete: Yadav A
Supervision in concrete constraction: Zutshi R and Singh N
Conceptualization, methodology, supervision, writing-review and editing: Jha M

Ethics Statement

Not applicable.

Consent for publication

Not applicable.

Availability of Supporting Data

Not applicable.

Conflict of Interest

All the authors declared that there is no conflict of interest.

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Supplementary

Table S1. Design mix for the preparation of M25 concrete

Design Mix	Ordinary Portland Cement (OPC) (Kg)	Rice straw Ash (RSA) (Kg)	Water(Kg)	Sand(Kg)	Coarse Aggregate (20 mm)	Coarse Aggregate (12.5 mm)	Water : (OPC + RSA)	(Cement + RSA): Sand: total coarse aggregate
1	5.1	1.5	2.7	9.18	18.42	-	~0.4	1:1.4:2.8
2	7.93	1.98	4.06	16.71	15.06	15.12	~0.4	1:1.6:3.04
3	10.36	2.59	5.19	19.78	18.08	18.08	~0.4	1:1.5:2.8

Table S2. FTIR bands of functional groups present in rice straw and rice straw ash

Wavelength (cm^{-1})	Functional group	Rice straw	Rice straw Ash
611, 782	symmetric stretching of Si–O bond	√	√
1042	Si–O–Si symmetric stretching	√	√
1647	Aromatic framework of the organic moiety	√	√
1970, 2049(Weak peak)	C–H stretching of CH_2 group	√	√
2154	–C≡C– stretching for hemicellulose	-	√
2850, 2919 (Intense peak)	aliphatic -CH_2 group	√	√
3340	O-H stretching vibrations of hydroxyl group	√	-

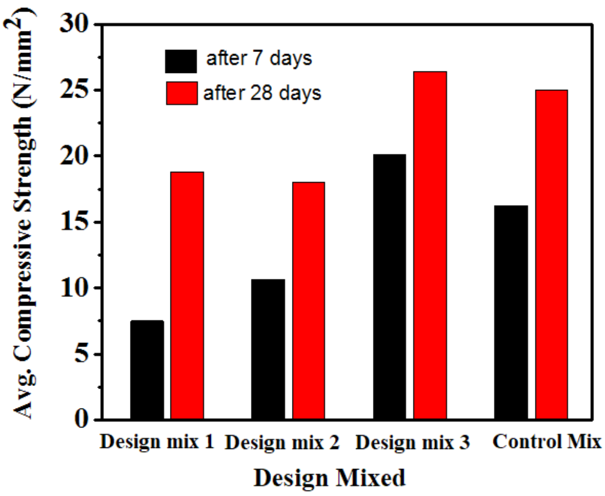

Figure S1. Compressive strength of M25 Concrete with various design mix