

Development of porous composite matrix using fly ash, waste tyre rubber, and rice husk ash for sustainable engineering applications

Abhishek Bisarya^{a,c}, Krishnakumar Bhaskaran^{b,c} & Ritesh Vijay^{a,c*}

^aCSIR-National Environmental Engineering Research Institute, Nagpur 440 020, Maharashtra, India

^bCSIR- National Institute for Interdisciplinary Science and Technology, Thiruvananthapuram 695 019, Kerala, India

^cAcademy of Scientific and Innovative Research (AcSIR), Ghaziabad 201 002, India

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Utilization of fly ash (FA), waste tyre rubber (WTR), and rice husk ash (RHA) has grown as research towards handling the disposal issue and its environmental degradation concerns. The present research and development has delineated a sustainable porous composite matrix utilizing industrial and agricultural wastes with minimal content of cement and water. The research study has included three phases of development such as FA-Cement; FA-WTR-Cement; and FA-WTR-RHA-Cement. Two optimized matrices FA-WTR-RHA-Cement (50%+20%+10%+20% and 50%+15%+15%+20%) by weight have exhibited density of 1.4 g/cm³, compressive strength of 8.0 and 8.8 N/mm², and system porosity of 61% and 60.5% respectively. FESEM and EDX have further validated a stable internal microstructure characterized by well-integrated waste particles, thereby improving the functionality of the matrix. A leachability study has also been carried out on the optimized matrices, with results well below the regulatory levels. Overall, the developed composite has offered a low-carbon, eco-friendly alternative to traditional materials, without any chemicals/additives, pre- and post-treatment of the waste, for sustainable civil and environmental engineering applications.

Keywords: Fly ash, Porous composite, Rice husk ash, Sustainable construction, Waste tyre rubber

1 Introduction

The accelerating waste generation from various sources presents significant environmental challenges, necessitating innovative waste management strategies¹. This escalating waste contributes to the generation of pollution on a large scale, underscoring the urgent need for sustainable practices that effectively mitigate these impacts². Utilizing industrial and agricultural by-products as substitute materials for engineering and environmental applications has been the subject of recent research³.

As per the report on fly ash generation at coal / lignite-based thermal power stations and its utilization in India issued by the Central Electricity Authority 2022, it states that coal-based thermal power plants are considered to be the keystone of power production and the country generated a huge amount of around 270 million tons of fly ash in the year 2021-22. It is considered one of the highly pozzolanic materials which makes it an effective and efficient partial replacement for cement in concrete production⁴. Its inclusion reduces the cement demand and enhances

the mechanical and engineering properties of concrete, contributing to more sustainable environmentally friendly construction practices⁵. Another plentiful industrial by-product that has attracted attention is waste tyre rubber, which may be used as a lightweight aggregate to increase the flexibility and durability of composite materials⁶. As per the report of Tyre & Rubber Recyclers Association of India (TRRAI) about 2 million MT of tyres are discarded as scrap annually. Rubber particles have been shown in recent research to enhance energy absorption and decrease brittleness in concrete⁷. Additionally, recycling used tyres reduces the environmental problems related to their disposal, which makes it an important part of a sustainable environment⁶. Apart from industrial waste rice husk/hull and rice husk ash are some of the major waste that is generated in huge amounts. Various reports stated that after China, India is considered to be the largest production of rice and produces around 120 million tons annually and after complete combustion, approximately 20-25% of Rice Husk Ash is produced⁸. Rice husk ash (RHA), a by-product of rice processing, is rich in silica and has potential

*Corresponding author (E-mail: r_vijay.neeri@csir.res.in)

applications as an eco-friendly material that can enhance the engineering and mechanical properties of concrete when used as a partial replacement for cement⁹. The incorporation of RHA not only contributes to the strength of concrete but also promotes sustainable practices by utilizing agricultural waste that would otherwise be discarded¹⁰.

Despite these advancements in using individual waste materials, there remains a significant gap in the development of composite matrices that maximize waste utilization while minimizing reliance on conventional cement¹¹. This research aims to formulate the design mix and develop a novel porous composite matrix with a unique combination of fly ash, waste tyre rubber, and rice husk ash with a minute quantity of cement blended with water in a novel way. Additionally, this research does not employ any chemicals or additives to obtain a proper homogenous mix as a result, the developed matrix will be more sustainable as it focuses on a zero-waste approach. The research is structured in three phases, which focus on optimizing the ideal compositions based on key engineering properties like density, compressive strength and system porosity.

2 Materials and Methods

This section comprehensively describes the materials used, design procedure, and evaluation of engineering properties including density, compressive strength, system porosity and also discusses morphological analysis of waste materials.

2.1 Materials

Class F Fly Ash was procured from a local thermal power plant, shown in Fig. 1(a) the main chemical constituents of class F fly ash typically include oxides of silicon, aluminium, and iron oxide with an equal to or greater than 70% by mass¹². When used as a partial

substitute for cement, its fine particle size and high silica and alumina content increase the pozzolanic activity of concrete, which in turn increases its strength, durability and workability¹³. Shredded rubber from end-of-life tyres, known as waste tyre rubber shown in Fig. 1(b) was utilized with particle sizes ranging from 1-2 mm. The chemical composition of waste tyre rubber majorly includes Carbon black and Styrene-butadiene rubber contributing to the maximum percentage¹⁴. Being a lightweight material with high resilience its inclusion aims to enhance the flexibility, durability and toughness of concrete composites and provides a sustainable option for lightweight porous structures¹⁵. Rice Husk Ash (RHA) falls under the category of agricultural wastes which is obtained from the burning of rice husks shown in Fig. 1(c). The typical chemical composition of RHA mainly includes reactive silica consisting of a major percentage¹⁶. Its high silica content makes it a valuable additive for improving the mechanical properties and durability of the composite¹⁷⁻¹⁸. Lastly, Ordinary Portland cement (OPC) was procured from a commercial supplier and was used as the binding agent as shown in Fig. 1(d). The chemical composition of OPC generally contains a maximum oxide percentage of calcium around 60% followed by silica around 20%, alumina around 7% and iron around 5%, the remaining contains Magnesia, Sulphur and Alkalis¹⁹. The calcium silicate phases in cement react with water to form hydration products that contribute to the strength of the composite.

The waste materials i.e. fly ash, waste tyre rubber and rice husk were also characterized using Field Emission Scanning Electron Microscopy (FESEM) and Energy Dispersive X-ray Spectroscopy (EDX). FESEM analysis was performed to investigate the micro structural and fracture behaviour, as this technique provides insights into the morphology and surface texture of the raw materials²⁰. On the other

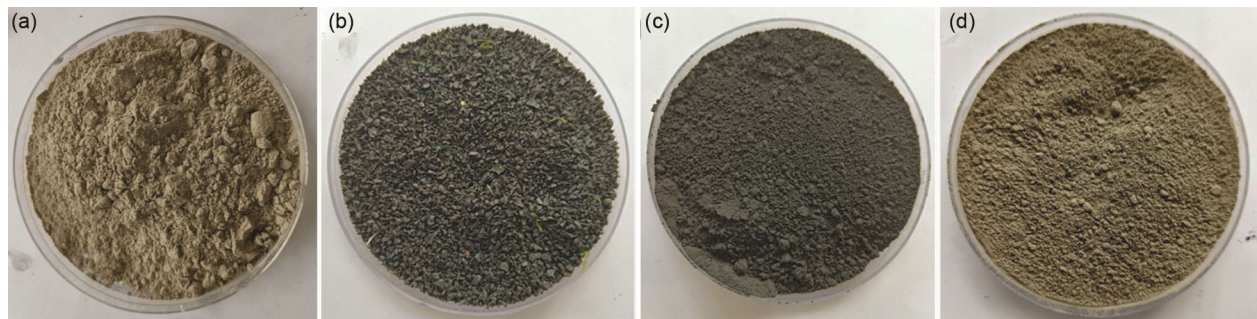


Fig. 1 — Materials used for the development of composite matrix (a) Fly ash, (b) Waste tyre rubber, (c) Rice husk ash and (d) Cement.

Table 1 — Composition of composite mixes by weight and water/material ratio.

Study	Composite	Compositions (by weight)				Water/ Material Ratio
		Fly Ash (%)	Waste Tyre Rubber (%)	Rice Husk Ash (%)	Cement (%)	
	C	0	0	0	100	0.36
Phase-I	FC1	30	0	0	70	0.32
	FC2	40	0	0	60	0.32
	FC3	50	0	0	50	0.32
	FC4	60	0	0	40	0.31
	Phase-II	FTC1	50	40	0	10
FTC2		50	30	0	20	0.24
FTC3		50	20	0	30	0.26
FTRC1		50	20	10	20	0.30
Phase-III	FTRC2	50	15	15	20	0.32
	FTRC3	50	10	20	20	0.35

* Where C= Cement, F=Fly Ash, T=Waste Tyre Rubber and R=Rice Husk Ash

hand EDX analysis was used to determine the elemental composition which enabled the identification of key chemical constituents that contribute to the overall performance of the composite materials²¹.

2.2 Development of composite

The raw materials were manually mixed to ensure a uniform distribution of particles, water was added to the dry mix until the desired workability was achieved. The obtained semi-solid mixture was poured into concrete cubes of size 15cm x 15cm x 15cm. After 36 hours the cubes were demoulded and submerged in water for 28 days curing to achieve optimal compressive strength. After 28 days of curing, the cubes were tested for density followed by compressive strength and system porosity. The study was carried out in three phases each with a specific purpose of evaluating the optimal performance of different combinations of raw materials, the details of various combinations of the composite mix are presented in Table 1 and the generic flow chart is presented in Fig. 2.

The first phase of the study focuses on the development of a composite matrix using fly ash and cement to identify the optimal percentage of fly ash that can effectively replace cement while maintaining acceptable mechanical properties. The purpose of the second phase of the study was to incorporate waste tyre rubber into fly ash and cement. As the fly ash percentage was optimized in the first phase, the percentage of cement and waste tyre rubber were altered in the study. The minimum cement percentage was also fixed depending on the mechanical properties. In the final i.e. third phase of the study, the goal was to explore the synergistic effects of incorporating all three waste materials fly ash, waste

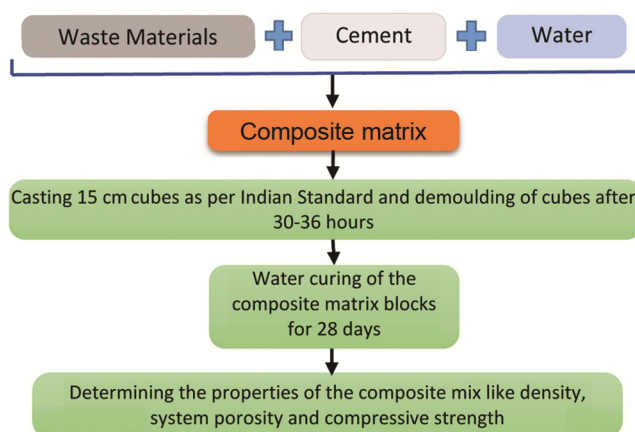


Fig. 2 — Flow chart of development of composite matrix.

tyre rubber, and rice husk ash properly and homogeneously mixed with a minimum percentage of optimized cement blended with water to obtain a composite matrix.

2.3 Evaluation of properties

The properties of the composite matrices were evaluated as per the Indian Standard Code Practices and compared with conventional matrices.

2.3.1 Density

The density of the composite was measured using the water displacement method (Archimedes' principle) using the Indian Standards^{22,23} [1199:1959 and 516 (Part 2/Sec 1):2018]. Density is calculated using Equation 1.

$$\text{Density } (\rho) = \frac{M}{V} \quad \dots (1)$$

M=Mass of the specimen (g)
V=volume of the specimen (cm³)

To determine the density of the composite, the mass of the specimen was measured using a digital

balance, and the volume was calculated based on the dimensions of the cube moulds.

2.3.2 Compressive strength

The tests were conducted using a compressive testing machine (CTM) in accordance with Indian Standard²⁴ (516 (Part 1/Sec 1):2021). Specimens were loaded until failure, and the maximum load was recorded.

The compressive strength of the composite was determined using Equation 2.

$$\text{Compressive Strength (fc)} = \frac{P}{A} \quad \dots (2)$$

P = Maximum load applied (N)

A = Cross-sectional area of the specimen (mm²)

2.3.3 Porosity

It is defined as the ratio of the volume of voids to the total volume of the material, expressed as a percentage. It is calculated using the following Equation 3.

The system porosity was calculated by filling broken specimens (20-50 mm size) in a graduated beaker filled with water and measuring the volume displacement as per Indian Standard²³ [516 (Part 2/Sec 1):2018].

$$\text{Porosity (P)} = \frac{V_v}{V_t} * 100 \quad \dots (3)$$

V_v = Volume of voids

V_t = Total volume of the broken specimen

The volume of voids was determined by immersing broken pieces of the specimens in water and measuring the displacement.

3 Results & Discussion

3.1 Physical properties of materials

The physical properties of the raw materials utilized in this study are crucial for understanding the behaviour of the developed composite matrix. Table 2 summarizes the density and porosity of each raw material.

The results indicate that waste tyre rubber possesses the lowest density (1.1 g/cm³) and highest porosity (55%), suggesting its potential to enhance the lightweight characteristics of the composite. Fly ash,

with a density of 1.4 g/cm³ and 45% porosity, serves as a valuable pozzolanic material, while rice husk ash contributes to overall silica content with a density of 1.3 g/cm³ and porosity of 42% which will help towards maintaining the decent compressive strength of the composite. Cement, although denser (1.5 g/cm³), provides the necessary binding properties for the composite matrix.

3.2 Material characterization

The micro structural characteristics of waste materials were analysed using Field Emission Scanning Electron Microscopy (FESEM) and Energy Dispersive X-ray Spectroscopy (EDX). FESEM images of fly ash revealed mostly hollow smooth particles with irregularly shaped particles with a glassy texture, indicating the presence of amorphous silica. The EDX analysis confirmed a high silica (SiO₂) content of approximately 26.1%, along with aluminium oxide (Al₂O₃) and iron oxide (Fe₂O₃), which contribute to its pozzolanic properties i.e. which enables them to blend freely in composite / mixtures, shown in Fig. 3a. The composition suggests suitability for enhancing mechanical properties in composites containing less percentage of cement. The FESEM analysis of waste tyre rubber showed rubber particles with irregular shapes, rough texture and porous structure, facilitating a lightweight composite. EDX analysis indicated a high carbon content of about 80%, alongside small percentages of sulphur (S) and oxygen (O). This unique composition enables the rubber to act as an effective lightweight filler while enhancing energy absorption characteristics in the composite. The FESEM and EDX analysis of waste tyre rubber is depicted in Fig. 3b and for rice husk ash, FESEM displayed silicate structure and flaky textures which generally indicates the surface is more loosely bound and can be highly reactive. EDX analysis revealed that rice husk ash contains significant amounts of silica (around 50%), contributing to its pozzolanic reactivity and promoting the formation of a denser microstructure in the composite. The FESEM and EDX analysis of Rice Husk Ash is depicted in Fig. 3c.

3.3 Engineering properties

Based on the results of composites in phase I, II and III, the engineering properties are determined in terms of density, compressive strength, water/material ratio and system porosity as presented in the following sections.

Table 2 — Density and porosity of raw materials.

Raw Material	Density (g/cm ³)	Porosity (%)
Fly Ash	1.4	45
Waste Tyre Rubber	1.1	55
Rice Husk Ash	1.3	42
Cement	1.5	30

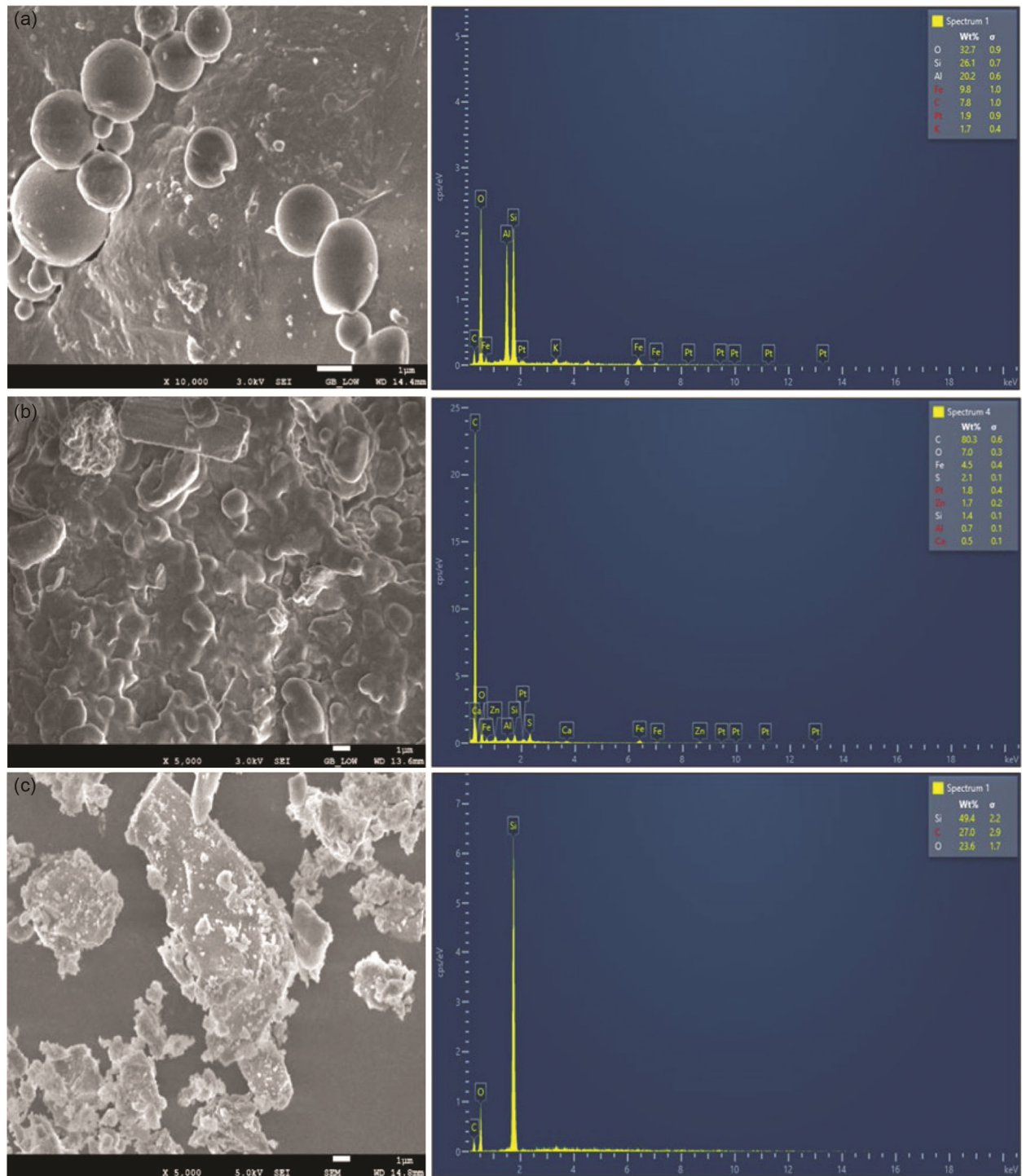


Fig. 3 — Raw material characterization (a) FESEM and EDX of fly ash, (b) FESEM and EDX of waste tyre rubber and (c) FESEM and EDX of rice husk ash.

3.3.1 Density

The findings indicate that as the cement content is reduced, the composite's density also starts declining. For instance, composite C, which is made completely of cement, has the highest density of 1.7 g/cm³ as

shown in Fig. 4a. On the other hand, in Phase I, composite FC4, which contains the highest percentage of fly ash (60%), resulted in a significant drop in density (1.4 g/cm³). This pattern is consistent with the fact that pozzolanic materials like class F fly ash used

in conventional binders typically result in low density²⁵. Phase II consists of 3 mixes FTC1, FTC2, and FTC3 from the results obtained, the introduction of waste tyre rubber significantly impacts the density. The lowest density was observed in composite FTC1 (1.2 g/cm³) consisting of 40% waste tyre rubber, 50 % cement, and only 10% cement. Lastly, in Phase –III

the decline in the density of the optimized composite matrix as compared with composite C, can be attributed to the inherent properties of fly ash, waste tyre rubber, and rice husk ash, which are less dense than cement. The lightweight nature of these waste materials helps in decreasing the composite mass, which is advantageous in reducing the load on

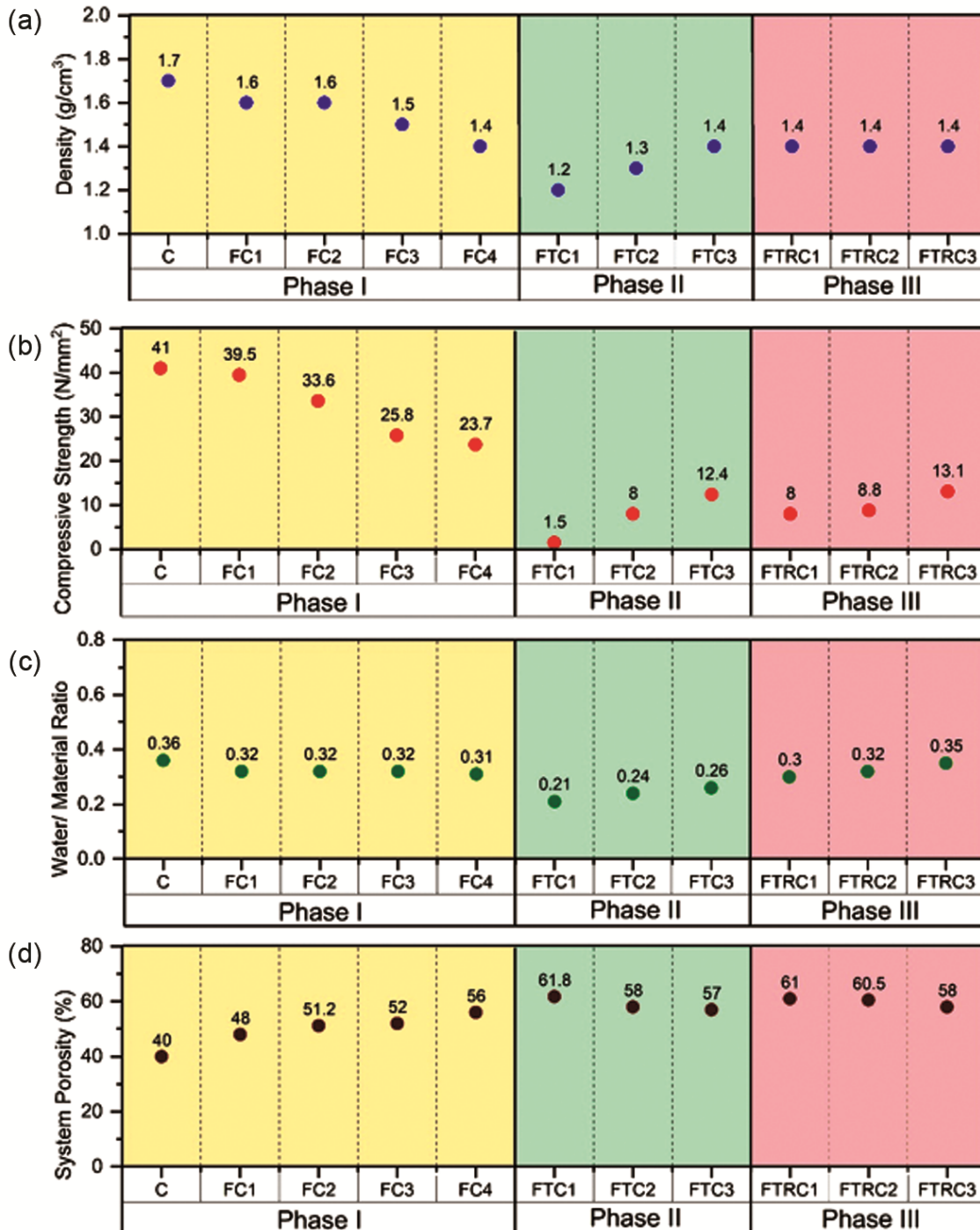


Fig. 4 — Engineering properties of the composites (a) Density, (b) Compressive strength, (c) Water/Material ratio and (d) System porosity.

structural elements in civil engineering applications, and also reduces the overall cost of the structure²⁶.

3.3.2 Compressive strength

The composite containing 100% Cement (C), exhibits the maximum compressive strength of 41 N/mm², which starts dropping after the inclusion of waste materials. In Phase I composite FC4 displays the lowest compressive strength of around 23N/mm², in Phase II FTC1 attains only 1.5 N/mm² compressive strength which is the lowest in all studies. This may be due to the very high rubber content of 40% weakens the internal bindings between the matrix and the very low cement percentage (10%) offers less binding capability thus lead to the drastic decrease in compressive strength²⁷. Phase III optimized compositions FTRC1 and FTRC2 maintain adequate compressive strength which is 8.0 and 8.8 N/mm² respectively as shown in Fig. 4b, that makes them suitable for structural and non-structural applications. Achieving satisfactory compressive strength may be due to high levels of reactive silica (SiO₂) and alumina (Al₂O₃) present in fly ash which probably reacts with calcium hydroxide which is formed during the hydration process of cement to form additional C-S-H gel thus increasing the structural integrity of the matrix²⁸. Rice husk ash also contains high silica which rapidly takes part in the hydration process. Furthermore, the fineness and high specific surface area in rice husk ash accelerate pozzolanic reactions contributing to the matrix's strength²⁹. As a result both materials i.e. Fly Ash and Rice Husk Ash, counterbalance the lower cement content which in turn lowers the carbon footprint.

3.3.3 Water/Material ratio

The water-to-material (W/M) ratio plays a vital role in determining the physical and engineering properties of composites. In this study, the W/M ratio was optimized to achieve adequate workability, uniform mixing, and desired porosity while maintaining compressive strength. From the results obtained, it can be seen that as cement content is reduced with waste materials, the W/M drastically reduced as the composite prepared with 100% cement attained a W/M ratio of 0.36, which is the highest in the overall study while the lowest W/M ratio is 0.21, achieved in composite FTC1 as shown in Fig. 4c. The optimal W/M ratio that guarantees adequate porosity, density and compressive strength is indicated by the optimized composites i.e. FTRC1 and FTRC2.

3.3.4 System porosity

The outcome of the study points out that, as cement content is reduced with waste materials the system porosity of the composite started increasing. This trend aligns with findings, where reducing cement in composite formulations results in a lower overall mass due to the inclusion of lighter materials²⁶. For example, the composite containing 100% Cement (C) achieved a system porosity of 40% which was the lowest in the overall study, in Phase I highest system porosity attained by FC4 (60% fly ash) which is 56%, while FTC1 conquered highest system porosity reaching up to 61.8% as compared with all the composites as shown in Fig. 4d. The highest porosity in FTC1 is due to the presence of rubber particles that not only contribute to a lightweight structure but also introduce additional large voids within the matrix, further enhancing porosity²⁷. Waste tyre rubber probably acts as an inert material as it does not react with cement and other pozzolanic materials, but the inclusion of waste tyre rubber introduces internal air pockets due to rubber's low density and porous nature, which increases the composite's overall porosity³⁰. Porosity is a critical parameter in this study, particularly for environmental applications such as media/substrate/filtration material in wastewater treatment technologies like constructed wetlands, trickling filters, etc as a replacement for naturally derived basaltic aggregates. Composites with higher porosity, such as those in the optimized composition, are well-suited for these applications which results in extended detention time which means more time for treatment of wastewater³¹.

3.4 Optimized matrices characterization

Based on the engineering properties, FTRC1 and FTRC2 were observed as optimized composites and they showcased similar images as there was a minute difference in compositions between the two optimized matrices. They exhibited distinct micro structural characteristics compared to the raw materials. FESEM images reveal a well-dispersed matrix in which the rubber particles are interlocked with ash particles, reducing the likelihood of interfacial voids and thus maintaining adequate compressive strength despite the high porosity. The absence of micro cracks and the homogenous dispersion of silica suggest effective bonding within the matrix, particularly due to the presence of fly ash and rice husk ash. These results corroborate the observed compressive strengths, as a dense microstructure typically enhances the composite's

load-bearing capacity. This synergy is further supported by EDX spectra that confirm a uniform distribution of all the elements across the composite matrix and the high silica content present in fly ash and rice husk ash maintains adequate compressive strength. The low calcium content aligns with the reduced cement proportion, yet the remaining structural integrity is attributed to the pozzolanic interactions between fly ash and rice husk ash. This micro structural compatibility supports the use of these composites in applications requiring both durability and permeability reflecting the contributions from the raw materials. Notably, the optimized composites retained high silica content while showing a significant reduction in cement content, illustrating the effectiveness of the waste materials in replacing cement without compromising the structural integrity. The FESEM and EDX analysis of the optimized composite matrix is presented in Fig. 5.

3.5 Leachability study

The Toxicity Characteristic Leaching Procedure (TCLP) test was conducted on the optimized matrices as per the USEPA Method 1311-TCLP, to assess whether heavy metals and other possible pollutants can leach into the environment from the developed matrices. As per the environmental safety concerns, the study required the test, as industrial and agricultural wastes such as fly ash, waste tyre rubber and rice husk ash may contain trace amounts of heavy metals.

The results obtained from TCLP, as well as the standard regulatory level, are presented in Table 3.

As per TCLP analysis, the concentrations of heavy metal contents in the leachate of optimized composite matrices (FTRC1 and FTRC2) are far below with

regulatory criteria, confirming their environmental benignity. These findings further enhance the composites' potential for widespread use as sustainable and safe substitutes for various environmental and civil engineering applications.

3.6 Sustainable development goals (SDGs)

By minimizing cement content and substituting it with a unique combination of industrial and agricultural waste, this study directly supports multiple Sustainable Development Goals (SDGs) like SDG 6 (Clean Water and Sanitation) through applications in wastewater treatment systems, SDG 9 (Industry, Innovation, and Infrastructure) by promoting new development from waste for infrastructure development, SDG 11 (Sustainable Cities and Communities) by the provision of materials suitable for permeable pavements, aiding in urban flood control and reducing surface runoff, SDG 12 (Responsible Consumption and Production) by repurposing waste materials into value-added products, promotes the concept of circular economy and SDG 13 (Climate Action) by promoting waste recycling, which reduces landfill use and mitigates environmental degradation.

Table 3 — Concentration of metals in leachate and regulatory limits.

Metal	FTRC1 (mg/L)	FTRC2 (mg/L)	EPA limit (mg/L)
Arsenic	<0.05	<0.05	5.0
Cadmium	<0.01	<0.01	1.0
Chromium	<0.02	<0.02	5.0
Lead	ND	ND	5.0
Mercury	<0.01	<0.01	0.2
Silver	<0.003	<0.003	5.0

*ND- Not Detectable

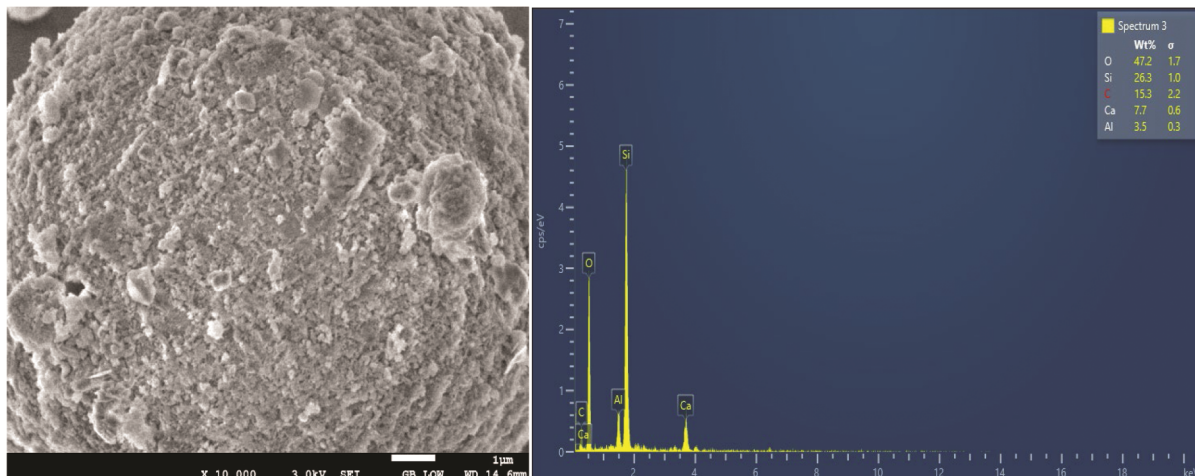


Fig. 5 — Optimized matrices characterization

3.7 Comparison with conventional porous composite

The porous composite matrix has attracted great attention across the globe, not only for the reason of its light densities ($1.0 - 1.6 \text{ g/cm}^3$)³² but also due to various advantages and a wide range of applications³³. The most common application is associated with a road shoulder material which enables it to collect the storm water runoff for groundwater recharge. Compared with the conventional composite having an impervious surface, preventing the rainwater from soaking into the soil, which disturbs the balance of the natural ecosystem³⁴. Also, most of the porous matrix contains a high percentage of cement which is highly unsustainable, as almost 1 ton of CO_2 is dispersed into the atmosphere due to every ton of cement production³⁵, hence there is an urgent need for an alternative porous material consisting of a smaller amount of cement. One such material is Autoclave Aerated Concrete (AAC) which is considered to be highly porous with a system porosity of 64%. For manufacturing AAC blocks requires a slurry that needs to be cured at a temperature and pressure above 170°C and 1.2 N/mm^2 respectively, with a time frame of 8 h after moulding. Such casting methodology consumes a massive amount of energy and cost³⁶. Looking at the overall scenario, the use of industrial and agricultural by-products in place of cement has been advantageous considering concrete properties and less impact on the environment. A viable option to accomplish the disposal of agricultural and industrial waste is to use them as supplementary cementitious materials (SCM) in a porous composite matrix³². The developed composite provides an eco-friendly, user-friendly, low-carbon emission and economically viable option that is in synchronization with nature, but unfortunately, very less research is available on the development of porous material/matrix/concrete utilizing a unique combination of industrial and agricultural by-products³³.

Hence, the developed matrices in the present study encompassed high porosity, low density and adequate compressive strength containing 80% waste material and 20% cement. The developed matrices have a wide and multi-range of applications as road shoulder material, partition wall, and filtration material in water and wastewater treatment plants which are not available in the literature. Although the system porosity of developed matrices is slightly low (61%) as compared with the obtained system porosity of AAC blocks (64%), the developed composites offer a clear advantage in terms of environmental protection,

preservation and degradation, consumption of natural resources and promotion of circular economy.

3.8 Future research

The findings of this research open several avenues for future exploration and application, which can further enhance the sustainability and performance of composite materials. The following are potential directions for future work:

- Carrying out long-term field studies to evaluate the durability and performance of the composites under various environmental conditions.
- Exploring the feasibility of scaling up the production of the composites at an industrial level.
- Performing a comprehensive life cycle assessment of the composites to quantify their environmental impact.
- Use of optimized composites in the mentioned applications such as use as media in constructed wetlands for treatment of municipal wastewater, permeable pavement material along the roadside for recharge of groundwater.
- Collaborating with regulatory bodies to develop standards and guidelines for the use of waste-derived materials in the civil and environmental sectors.

4 Conclusion

A novel composite matrix has been designed and developed with high porosity and adequate compressive strength, using a unique combination of fly ash, waste tyre rubber, and rice husk ash with minimal cement content and water as the sole binder. The two optimized composite matrices FTRC1 and FTRC2 attained water material ratio (0.30 & 0.32), density of 1.4 g/cm^3 , adequate compressive strength (8.0 & 8.8 N/mm^2) and high system porosity (61% & 60.5 %). The study demonstrated a significant reduction in cement content resulting decrease in density and an increase in porosity of the composite matrices. This is attributed to the incorporation of highly porous waste material, i.e. waste tyre rubber which increased the internal void structure, while the compressive strength was maintained through the pozzolanic material i.e. fly ash and rice husk ash, as they are highly reactive due to the presence of high silica content. Field Emission Scanning Electron Microscopy (FESEM) and Energy Dispersive X-ray Spectroscopy (EDX) analyses provided insights into the microstructure and elemental composition of raw materials and the optimized composite matrices. These analyses confirmed

the formation of a stable matrix with uniformly distributed waste particles, contributing to the composite's structural integrity and functional properties. The optimized composite matrices also went through the TCLP test with values well below the prescribed limits. The development further provides non-chemical, non-energy, eco-friendly and cost-effective composite matrices for various civil and environmental engineering applications. Due to the huge reduction in cement and utilization of industrial wastes and agricultural by-products, the optimized matrices offer a pathway of low carbon emissions for sustainable development. This development supports the United Nations Sustainable Development Goals by promoting waste utilization and a circular economy.

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