Indian Journal of Engineering & Materials Sciences
Vol. 30, February 2023, pp. 94-102
DOI: 10.56042/ijems.v1i1.63323

Design and development of light weight porous matrix using industrial waste

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Received: 17 May 2022; Accepted: 27 September 2022

The aim of the current study is to optimise the composite mixture of fly ash, rubber waste and Ordinary Portland Cement (OPC)for the design and development of a light weight porous matrix. The composite matrices have been evaluated based on the engineering properties consisting of compressive strength, density, open porosity (VR%) and water-material ratio (WM%). The Scanning Electron Microscopy (SEM) is used for the observation of the microstructure of cement, tyre rubber granules, fly ash and the optimized composite matrix. The compressive strength and density decrease with the increasing quantity of waste tyre rubber granules in the matrix, whereas the porosity of the matrix enhances. Since, the rubber granules act like voids in the composite matrix, results into the development of light weight porous matrix, which is also confirmed by SEM analysis. The study confirms the usability of the composite matrix aslow-cost partition walls or low load bearing structures. The utilization of the waste material reduces the land requirement for huge disposal site as well as reduces the carbon footprint due to the reduced utilization of cement. The composite matrix can be further utilized through proper design mix with additional construction materials such as fine and coarse aggregate to broaden the applications horizon in civil and environmental engineering.

Keywords: Composite matrix, Fly ash, Industrial waste, Light weight material, Porous material, Waste tyre rubber

1 Introduction

Nowadays, the world is concentrating on sustainable development by minimizing the CO_2 emissions. About 10% of CO_2 emissions levels have originated due to cement production[1]. The demand for construction materials is increasing with the fast-growing population at the global level. As a consequence, the raw materials are exhausting rapidly and the cost of natural resources is rising at the same time[2]. Hence, many industries have attempted to shift from the conventional materials towards green materials by minimizing the utilization of cement. This may be achieved by reusing the industrial waste and its by-products such as fly ash, rice husk, tyre rubber, plastic etc. According to the environmental policies, industrial waste materials should be treated before releasing into the landfills. Treated waste materials can be utilized in the construction industries with replacement of cement in the design mix, which also proves to be economically viable[3]. Favourable applications of waste materials reduce the land requirement of the huge disposal site and also provide inexpensive resources for other manufacturing purposes. The multiple applications encourage cleaner production by decreasing the emissions levels. Disposal of coal combustion products and Waste Tyre Rubber (WTR) is a serious concern for the world. There is a dire need to explore the alternatives where the residue of coal combustion and WTR can be utilized[4].The present study focuses on the utilization of fly ash and WTR with blended cement paste for the development of the light weight design mix rendering multiple applications.

As per Wang *et al.* 2020[5], an estimate of approximately 600-800 million tons of fly ash is generated worldwide on yearly basis. Fly ash has been utilized in the construction industries from the past 50 years but in a finite way because of insufficient knowledge regarding the characteristic of fly ash and properties of construction materials assimilating fly ash[6]. The use of fly ash to replace cement in the production of concrete is now considered to be the newest trend[7]. Multiple studies on preparing concrete and mortar by inclusion of fly ash has been performed by many researchers[2,7-10]. The annual production of fly ash in India is approximately 88 million tonnes out of which only 10 to 15 % is reused[11]. Fly ash is the main residue product of the coal combustion which is

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collected from the boiler of the power plant by using electrostatic precipitators or mechanical separators. The main constituents of fly ash are oxides of aluminium, silicon, iron, sodium, potassium, calcium, magnesium and sulfur[12]. Based on chemical composition, fly ash is categorized into two classes viz Class C and Class F which are also proposed by Indian standard(IS:3812 2013)[13].In India, Class F fly ash is abundantly produced, which contain more than 70 % of the sum of oxides of silicon, aluminium and iron[11].

Fly ash is used in many constructions work and industries due to good cementitious and pozzolanic characteristics. The utilization of fly ash is environmentally and economically feasible for construction as it renders good mechanical properties[12]. Mixing of fly ash with cement in the presence of water results in to pozzzolonic reaction between $Ca(OH)_2$ (Calcium hydroxide) which is produced by hydration of cement and glassy part of fly ash. That pozzolanic reaction leads to the production of Calcium silicate hydrate (C-S-H)gel and provides greater density as well as strength[14]. The compressive strength of concrete made by using fly ash with cement increases with concrete age[6]. The fineness and quantity of fly ash influences the porosity and pore size of the design mix of the cement and fly ash blend. The density and strength of the mortar are higher when the finest fly ash is blended with cement as fine fly ash is highly reactive[15]. The advantages of blending fly ash as a partial replacement of cement in the design mix are reduced water demand for uniform workability, decreased bleeding and prevention of cracking at the initial stage by managing the expansion of heat of reaction (hydration) [16-17].

The demand for the rubber tyre is increased due to the rapid development of the automobile industry. Approximately 1.2 billion waste tyres are discarded worldwide every year due to their short life span[18]. In which, only 4% of waste tyres are reused in the civil engineering field, 11 % areexported and 27 % are sent for dumping yard for landfilling[19]. India accounts for 6–7% of the global amount of waste tyres. Local tyre industries have been expanding at a pace of 12% annually, and the volume of waste tyres is escalating. India has been reusing and recycling old tyres for almost four decades, but just an estimate shows that 60 % of them are abandoned or buried illegally[20]. Tyre rubber is a non-biodegradable product so it cannot be easily destroyed even after a long period of land filling practice[21].Landfilling of WTR is a serious problem for the environment because of its structure and impermeable nature. Due to water retaining characteristics it becomes a shelter for insects and organism which create further problem for a human being[22,23]. Another cheapest disposal method of tyre rubber is burning which can cause environmental pollution because it releases toxic gasses and oil into the environment that further pollutes the air and soil respectively[24]. Therefore, there is a dire need for research and development towards increasing the applications of WTR in multiple sectors. Tyre rubber contains three main components namely synthetic fibre, steel wire and rubber. A typical tyre has a 9.1 kg weight in which 22 % of the total weight is fibre, steel wire contains 18 % of the weight and 60 % isreclaimed rubber. Reclaimed tyre rubber has 65 % synthetic rubber and 35% natural rubber[25].

In the present research study, the matrix has been designed and developed by utilization of industrial wastes i.e. Class F fly ash and WTR granules, blended together with the help of cement. The physical and mechanical properties of the designed matrix are evaluated and interpreted for various applications in multiple sectors.

2 Materials and Methods

This section elaborates the materials and methods adopted for the present research study.

2.1 Materials

In the present research, mainly three materials including cement, fly ash, tyre rubber particles are blended with the help of water under different proportions for preparation of samples. The rubber granules used in the present research study was derived from the grinding and winnowing process of WTR as shown in Fig. 1(a). Different sizes of rubber granules were available but only 1 to 2 mm particle sizes were used for investigation. Rubber granules have low specific gravity which varies from 0.51 to 1.2 and low density which varies from 0.524 g/cm^3 to 12.733 g/cm^3. Rubber granules have low water absorption capacity; by means, it is hydrophobic in nature which entraps air in the structural voids[26]. X-Ray Fluorescence (XRF) method was used for determination of chemical composition for WTR according to ASTM 5381-93. The two major chemical constituents found in the WTR were

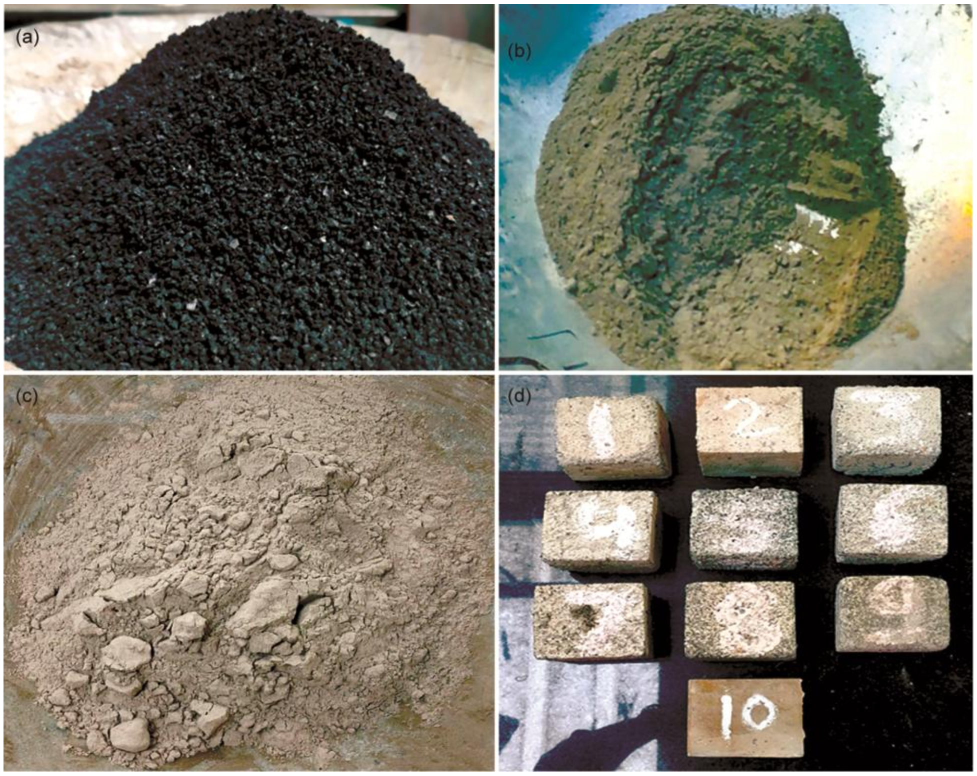

Fig. 1 — Materials used in development of the composite matrix a) Tyre rubber granules, b) Cement, c) Fly ash, and d) Composite matrix with varied combination of a , b and c.

styrene-butadiene rubber (49.1%) and carbon black (46.2%) which combinedly acquired 95.3% composition. Other constituents included zinc oxide, extender oil, accelerator, stearic acid and sulphur.

Ordinary Portland cement (OPC) was usedas a binder which is of Grade-33 asrecommended by Indian standard IS: 8112-2013 (Bureau of Indian Standard(BIS) 2013)[27] having specific gravity of 3.15 as shown in Fig. 1(b).

The Class F type of fly ash as shown in Fig. 1(c), was derived from the coal combustion plant in the Koradi thermal power plant located about 20 km in the north of Nagpur city, Maharashtra, India. The chemical composition of fly ash was revealed dominance of silicon dioxide (55.3%), aluminium oxide (25.7%), ferric oxide (5.3%) and calcium oxide (5.6%) acquiring 91.5% of fly ash composition. Other secondary constituents' materials include oxides of magnesium, titanium, potassium and sodium. Portland cement, hydrated lime or quicklime are formed by the reaction between water and Class F fly ash[28]. The utilization of fly ash rendered two major advantages i.e. reuse of fly ash as a substitute material in the design mix and also reducing the cement content in the design mix. Normal tap water was used for mixing all material and to hydrate the cement for the design mix.

2.1.1 Preparation of samples

The research study was carried out in majorly two phases. In the first phase, the design mix was prepared by mixing the rubber granules with cement and gradually increasing the percentage of rubber granules in the mixture. For this, the cement and rubber granules (1 to 2 mm) were dry mixed manually and then water was added till a homogenous mixture was prepared. For the required consistency of the blended paste, the quantity of water was varied for different proportions as given in Table 1.

After the preparation of homogenous paste, it was casted in the required sized mould. For evaluation of the physical and engineering properties, cubical moulds of size 7.5 cm x 7.5 cm x 7.5 cm were used as shown in Fig. 1(d). For efficient compaction of materials, the moulds were placed in vibrating table. After the casting, it was left for 2 days for solidification; afterwards it was removed from the moulds and retained for curing process at ambient temperature using normal tap water till its testing days. The cubes were tested for the compressive strength at 3,7,14 and 28 days on each composite

Table 1 — Different composition of samples

Sample Code	Rubber (%)	Cement (%)	Fly ash (%)
RC1	10	90	0
RC2	20	80	0
RC3	30	70	0
RC4	40	60	0
RC5	50	50	0
RC6	60	40	0
RCF1	50	40	10
RCF2	50	30	20
RCF3	50	20	30
RCF4	50	10	40

matrix and average value of compressive strength is reported based on 3 tested cubes of each mix.

In the second phase of the study, the percentages of rubber granules were fixed while the percentage of OPC and Fly Ash was varied as given in Table 1. The same methodology for the preparation of the sample was adopted as mentioned above.

2.1.2 Water-material ratio (WM%)

The quantity of water plays an important role on initial and final setting time of the matrix. The strength of the material is directly affected by the water- material ratio. Lower water-material ratio indicates longer durability and higher strength. Fly ash and cement were dried at 105 ºC in an oven before use so it can be ensured that both the materials were free from moisture. The Water-material ratio was evaluated by the measurement of the volume of water upon the weight of total material in the mixture as shown in Equation 1.

$$WM\% = \frac{water}{Cement + Fly\ ash + Tyre\ rubber} \quad \ldots (1)$$

Where volume of water is in ‘ml’ and weight of material is in ‘grams’.

Normal tap water is used for binding the rubber particles with the cementitious material. Hence, the quantity and quality of water used will surely affect the fresh setting and hardening properties, which will majorly impact the compressive strength and porosity of the material. The quantity of water required for binding the materials majorly depends on the required consistency of the mixture. The amount of water was such used so that the final mixture is nor too wet or not too dry while maintaining an efficient consistency of the mixture.

The highest WM% i.e. 0.42 was observed for sample RC1 as it consists highest percentage of cement by weight with respect to other samples i.e. 90% cement with 10% rubber particles. In first phase of the study, for the samples from RC1 to RC6, the percentage of cement was constantly reduced with the interval of 10% and simultaneously compensated with rubber particle. As the portion of cement is reduced and compensated with the portion of rubber particle, the WM% is slightly decreased due to reduction in the quantity of cement. The WM% for samples RC1 to RC6 varied between 0.31 to 0.42.

In the second phase, the portion of cement was further reduced and replaced with fly ash. Since the binding properties of cement and fly ash is similar with respect to the water content, the WM % does not fluctuate significantly for the samples RCF1 to RCF4. The WM ratio was observed to be in the range of 0.36 to 0.38 for samples RCF1 to RCF4.

2.2 Methods

The methodology adopted for analysis of mechanical properties of the matrices such as density, void ratio, compressive strength with microanalysis of the structure using the scanning electron microscopy test is elaborated below.

Density (ρ)

Density was calculated by the measurement of mass (m) of sample upon volume (v) as shown in Equation 2. Volume was considered as the volume size of mould is 7.5 cm x 7.5 cm x 7.5 cm.

$$\rho = \frac{m}{v} \quad \ldots (2)$$

2.2.1 Void Ratio (porosity)

The void ratio was evaluated by the vacuum water saturation method as prescribed in European Committee for Standardization[29]. First of all, samples were air dried at a temperature of 105 ± 5 ºC in an oven for 24 hours. The initial weight (W_1) was taken with help of weighting balance for all samples and then left underwater for 24 hours in a vacuum container till the attainment of saturation level of the samples. Subsequently, samples were taken out from the water and then weighted (W_2) again.

The void ratio (VR %) was evaluated as per Equation 3.

$$VR\% = \frac{Vw}{Vs} * 100 \quad \ldots (3)$$

Where V_w is the total volume of water occupied in samples and $\mathbf{V_s}$ is the total volume of sample. The volume of water occupied in samples (V_w) can be calculated as per Equation 4.

$$V_w = \frac{W_2 - W_1}{\rho w} \quad \ldots (4)$$

Where W_1 and W_2 are the initial and final weight of samples respectively and ρw is specified as the density of water.

2.2.2 Compressive strength (CS) test

The compressive strength test is performed to assess the ability of the material to endure pressure before its breaks down. The compressive strength of samples was carried out using cubical moulds (7.5 cm x 7.5 cm x 7.5 cm) as specified by Indian standard (IS 516 1959)[30]. Prepared cubes mould was used for the testing of compressive strength.

Compressive test for the developed material was carried out for 3, 7, 14 and 28 days respectively. For each sample, 3 separate cubes were prepared which were tested for compressive strength after 3, 7, 14 and 28 days respectively and average strength of 3 cubes were considered as the final strength of the respective sample.

2.2.3 Scanning Electron Microscopy (SEM) test

SEM method is specifically surface sensitive. SEM was used for the investigation of the microstructure of cement,tyre rubber granules, fly ash and the composite matrix. The very small quantity of samples is carried by gold plating for scanning electron microscopy. Morphology of any particles is used to define the physical and mechanical characteristics of the respective materials.

3 Results and Discussion

The physical and mechanical properties of the developed matrix are explained and interpreted with the microstructure of all components of the composite matrix.

3.1 Density (ρ)

A higher density is observed for sample RC1 is 1336.9 kg/m^3 because it is prepared by 90% cement with 10% tyre rubber granules. RC2 (80% cement with 20% rubber), RC3 (70% cement with 30% rubber), RC4 (60% cement with 40% rubber), RC5 (50% cement with 50% rubber) and RC6 (40% cement with 60% rubber) have density in decreasing order is 1073.8kg/m^3, 1057.2kg/m^3, 855.7kg/m^3, 794.1 kg/m^3 and 663.7kg/m^3 respectively. The density of composite matrix is diminished by increasing the quantity of tyre rubber. The density of samples is presented in Fig. 2.

The composite matrix prepared by using cement, fly ash and rubber rendered density in descending order. Density of RCF1(50%rubber+ 40% cement +10% fly ash) is 813kg/m^3 that is approximately similar to RC5, both have same quantity of tyre rubber granules but in RCF1 only 10 % cement is replaced by fly ash. RCF2 (50% rubber+ 30% cement + 20% fly ash), RCF3 (50%rubber + 20% cement + 30% fly ash) and RCF4 (50%rubber + 10% cement + 40% fly ash) possess density is 749 kg/m^3, 732.4 kg/m^3 and 730.1kg/m^3. There is not much difference in density of RCF2, RCF3 and RCF4, it may be stated that the density is not greatly influenced by replacing the cement with fly ash; it confirms the efficient replacement of cement with fly ash in the composite matrix. Due to low density of rubber particles, the developed composite matrix's density also reduces, as the rubber granules are increased in the matrix. Prepared composite matrix becomes lighter in weight by utilization of rubber granules in the design mix hence this light weight material can be used in many civil and environmental engineering applications such as partition wall and barriers.

3.2 Void Ratio (VR%)

The void ratio increases as the proportion of tyre rubber granules and quantity of fly ash increases. The void ratio of RC1 is 5.9% which is the lowest ratio it may be possible due to this being made by 90% cement with less quantity (10%) of tyre rubber

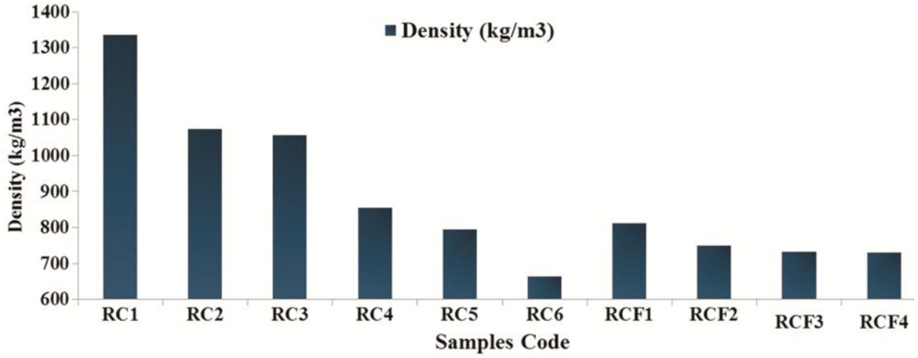

Fig. 2 — Density of the composite matrices.

granules. It is observed that RCF4 possess the highest porosity is 28.4% among all samples. Successively, porosity of RC2, RC3, RC4, RC5 and RC6 is 8.5%, 9.0%, 14.2%, 19. 7% and 23.9% respectively. The porosity increases with the increased quantity of tyre rubber granules. It may be attributed due to tyre rubber granules themselves having voids that entrap air on their surface. Void ratio or porosity of composite matrix is shown in Fig. 3.

The composite matrix which is prepared by using fly ash, rubber and cement blend has enough porosity. The porosity of RCF1, RCF2 and RCF3 is 16.8%, 19.4% and 23.5% respectively. The rubber content is fixed for the samples RCF1 to RCF4 i.e. 50%, only cement content is replaced with fly ash. The replacement results into increment in the void ratio of the samples. Porosity is increased by increasing the quantity of WTR granules as the rubber granules act like voids in the composite matrix. As the numbers of granules are increased, the voids are also increased rendering development of highly porous composite matrix.

3.3 Compressive strength

The results of the compressive strength test of samples after the interval of 3, 7, 14 and 28-days curing are shown in Fig. 4. Sample RC1 has higher compressive strength at the ages of 3, 7, 14 and 28 days is 20.1 MPa because RC1 is prepared by 90% cement with 10% tyre rubber granules. Following, RC2 in which cement is 80% and tyre rubber granules is 20% compressive strength is reduced till 16.3 MPa. From mix design at the age of 28 days, RC3 possess slightly lower compressive strength is 10.5 MPa as compared to both RC1 and RC2. Subsequently, RC4, RC5 and RC6 have compressive strength in descending order is 8.5 MPa, 7.0 MPa and 5.5 MPa respectively, it may be attributed by increasing the quantity of tyre rubber granules along with decreasing quantity of cement.

Composite matrix is also prepared by adding fly ash as a replacement of cement with constant quantity (50%) of WTR granules. Rubber granules are kept 50% because at this stage compressive strength is found to be 7.0 MPa which is feasible for partition walls or low load-bearing structure elements.When adding further tyre rubber granules (60%) in design mix, composite matrix becomes brittle.

The sample RCF1, RCF2, RCF3 and RCF4 possess compressive strength in declining order is 6.8 MPa, 6.4 MPa, 6.1 MPa and 5.3 MPa. It is observed that the

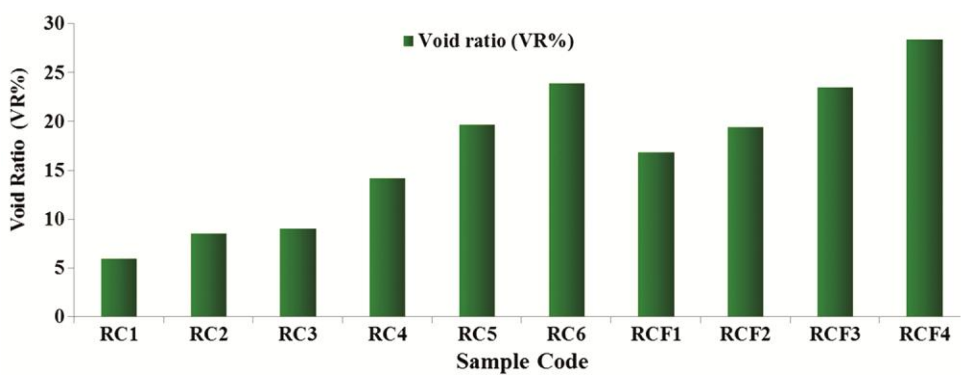

Fig. 3 — Void ratio (VR%) of the composite matrices.

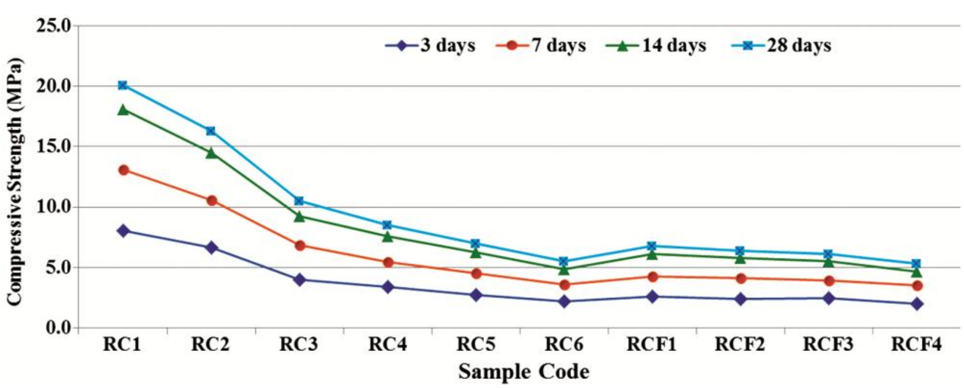

Fig. 4 — Compressive strength of the composite matrices.

compressive strength of rubber, fly ash and cement blend is decreased with the increasing quantity of tyre rubber granules and decreasing quantity of cement.

Comparing samples RC6 and RCF4, it may be noted that replacement of cement with fly ash reduces the compressive strength by 3.6% only, hence only a mere reduction is observed. Moreover, the void ratio is increased by 18% for sample RCF4 as compared to RC6. Therefore, the replacement of cement with fly ash proved to be efficient with respect to the development of light weight porous matrix.

It may be attributed that the tyre rubber granules possess lower strength as compared to cement matrix due to binding property of cementitious particles. As the rubber percentage is increased in the matrix, the bond formed between the rubber granules and cement does not remain robust hence cracks are appeared first in the contact zone as heavy force is applied. The crack gets easily propagated and result into the breakdown of the matrix.

3.4 Microstructure of materials and composite matrix

SEM tests showed that tyre rubber granules have an irregular shape and smooth surface textures with numerous voids, when observed under 9.98kx magnifications with view field is 13.9 µm as shown in Fig. 5(a). It shows some pores, cavities and cracks on the surface of rubber granules. Microstructure of Grade 33 cement used in the composite matrix was observed under magnification of 3.00 Kx in view field of 46.1 µm as shown in Fig. 5(b). Major spherical structures (cenospheres) are observed with distorted irregular shapes. The irregular spikes rendered high binding capability due to presence of high interlocking surface area resulting in to stronger bonds. Due to clumpy surface texture of rubber particles, blending with cement particles develops a

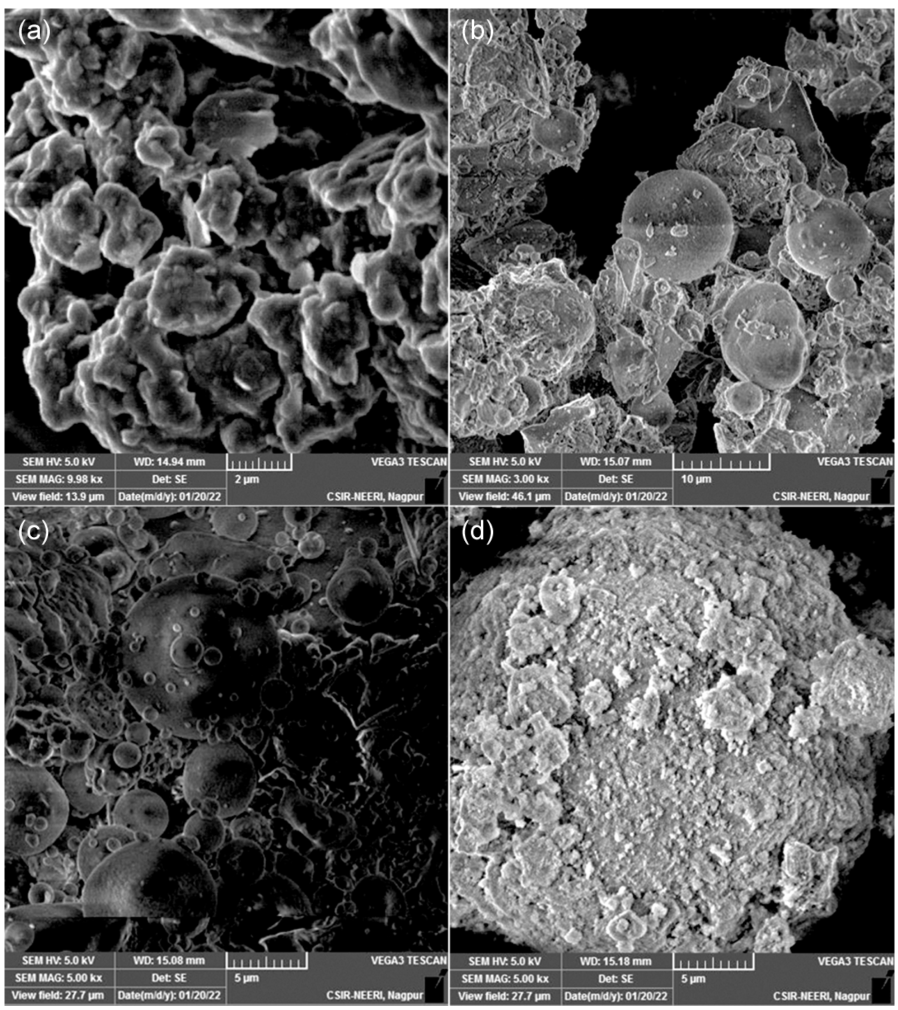

Fig. 5 — Micro-structure of materials observed on SEM imageof a) Tyre rubber granules, b) Cement, c) Fly ash, and d) Composite matrix (RCF4).

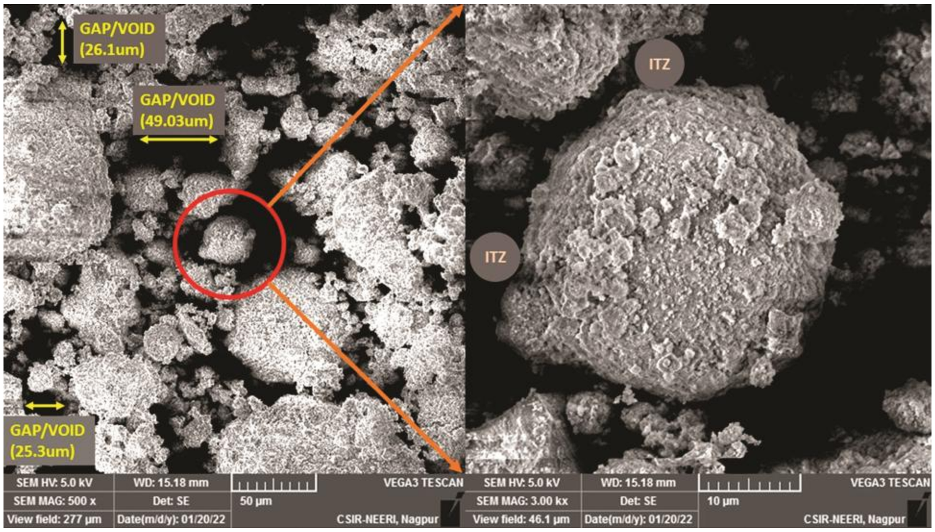

Fig. 6 — Formation of void and interfacial transition zone in the composite matrix.

weaker interlocking bond. Due to clumpy texture of rubber particles, it was not feasible to increase the rubber content in the design mix above the 60%, as shown in Table 1. As further replacement will result in a weaker overlapping bond with cementitious material due to the low availability of surface area for establishment of bond. Hence, adhesion between cement matrix and rubber granules is weaker. Due to the available number of voids, the air is entrapped on its surface as well as in the internal matrix of material.

Microstructure of fly ash was observed with magnification of 5.00kx with view field is 27.7 µm. the image field is dominated by cenospheres of multiples sizes varying from 0.59um to 10.31µm as shown in Fig. 5(c). Due to common cementitious properties between cement and fly ash and similar microstructure, the bond cannot be developed between both the materials, when mixed in presence of water. Due to high SiO_2 content in fly ash, the formation of C-S-H fraction decreases the porosity on the composite matrix. Small cenospheres sizes ensure high and efficient reactivity of fly ash with other material in the composite matrix. Due to this, a high percentage of cement was replaced with fly ash without causing many disturbances in the strength of the composite matrix.

For examination of binding properties and changes brought by the mixing of cement, fly ash and rubber granules, the SEM image of composite matrix was observed under magnification of 5.00 kx and view field of 27.7µm for the sample RCF4 as shown in Fig. 5(d). The size was abnormally enlarged resulting in to a larger clump of rubber particles surrounded by fly ash and cement giving sufficient bond strength and efficient interlocking of materials. Small pore of various sizes can be observed on the surface texture. As the materials are blended with help of water which activates different chemical elements, hence resulting in to efficient bonding between materials.

In the developed RCF4 matrix, there is no specific interfacial transition zone (ITZ) observed due to absence of aggregates, but large clumps of particles encapsulated by cement and fly ash matrix (Fig. 6). Since, the void ratio is quite high in the developed matrix, the formation of numerous interlinked multi-dimensional voids is observed, which conveys that the composite matrix is highly porous and light weighted.

4 Discussion

The research study for the development of a lightweight porous matrix succeeded in replacing a larger portion of cement content with fly ash and rubber particles in the matrix. The density of the composite matrix decreases by the successive increase in tyre rubber granules and fly ash percentage. The tyre rubber granules size ranged from 1-2 mm, ensuring adequate bonding between the cementitious matrix (fly ash and cement) due to small particle size providing effective surface area.The tyre rubber granules and fly ash themselves have a lower density and specific gravity as compared to cement. Porosity is increased by utilization ofWTR granules because when the rubber particles are mixed with other elements, voids are introduced in the internal structure of the composite material. Hence the increment in the voids renders formation of highly porous and lighter material. The rubber content was kept high to maintain the porosity in the composite matrix as increases in porosity constituent lower weight of the structure. But due to unwieldy texture of rubber granules, it was not feasible to raise the rubber content in the design mix above the 60%, as it will result into formation of weaker bonds due to inefficient mixing of the material. The weaker interlocking bond decreases the strength of the composite matrix but increases its porosity, but due to requirement of minimal strength for the matrix, rubber was fixed at 50% for further addition of fly ash. The further replacement of cement by fly ash, in the second phase of the study, merely affected the compressive strength of the matrix but enhanced the void ratio significantly. The developed matrix for RCF4 consist of 50%rubber particles, 10% cement and 40% fly ash, which renders the maximum utilization of industrial waste, enhancing the economic and environmental aspect for further utilization of the matrix.

5 Conclusion

In the present study a composite lightweight and porous matrix by using industrial waste namely WTR granules and fly ash, as a major replacement of cement have been developed. The developed matrix can be used in non-load-bearing structures, which will also serve as an efficient management strategy towards bulk reuse of industrial waste. The compressive strength of the matrix reduces with an increase in the percentage of rubber granules in the matrix. But still, adequate strength is provided by the matrix for its further applications in the form of lightweight non-load-bearing structural elements. The matrix also serves as an economical as well as a viable alternative resource for construction industries for various applications such as partitioning walls, paver blocks, and top layering of pathways where the upcoming load expected is quite lower.

The industrial waste products used in the research study i.e. fly ash and rubber granules generally ends up in the landfill due to lack of technical solutions and improper management, hence risking further contamination of the environment. Reuse of industrial waste and reduction in cement content for the development of lightweight matrix reduces the carbon footprint by extending the applications of industrial waste and its by-products. It also ensures the reduction in the demand for dumping sites for the disposal of the respective material. The formation of interlinked multi-dimensional voids in the matrix can be further optimized for its application in noise attenuation and wastewater treatment, as an extended application horizon in the environmental sector.

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