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Research Article

Value-added waste substitution using slag and rubber aggregates in the sustainable and eco-friendly compressed brick production

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Abstract: The current study aimed to analyze the viability of incorporating the post cryogenic discarded rubber and the air-cooled slag as an aggregate in partial replacement of stone dust in fly ash bricks production. A range of mechanical, non-destructive, and microstructural tests was performed on bricks thus produced by incorporating rubber and slag aggregates in various dosages (i.e., 5, 10, 15, 20 and 25% by stone dust weight). The result revealed that the compressive strength dropped from 71 to 43 % in the case of rubber aggregate replacement. Morphology study confirms that the rubber aggregates resulted in the porous microstructure of the bricks and thus leads to lesser unit weight and lighter structure. The rubber may be used as a lightweight aggregate in the brick possibly as it reduces the density of the final product. However, the use of rubber in bricks needs to be cautiously designed to get hold of productive solutions at the end. The findings demonstrate that the copper slag substitution of up to 15%, found to be enhanced the strength properties and it will be a better choice for low-cost construction as a promising alternative construction material.

Keywords: rubber aggregate; copper slag; recycled waste; mechanical properties; microstructure.

1. Introduction

Currently, the most significant problem encountered by a human is to conserve natural resources effectively and efficiently (R. Prakash, Thenmozhi, & Raman, 2019; R. Prakash, Thenmozhi, Raman, Subramanian, & Divyah, 2021). Also, the waste materials accumulating on a day-to-day basis from industries needs to be removed by solid waste management. With the strict environmental legislation, the small and big construction products manufacturing firms are anticipating the other quick fix with the aim of recycling and adding financial benefits to the final products are ever increasing (Nirmala & Viruthagiri, 2014). With the existing research, it is suggested to use the industrial wastes to transform into any alternative products are the viable solutions (Divyah, N, Thenmozhi, R, Neelamegam, M, 2020; Nagarajan, Rajagopal, & Meyappan, 2020; Praburanganathan

& Chithra, 2020; Ramaiah Prakash, Thenmozhi, Raman, & Subramanian, 2020) for this problem. The construction sector is the principal area having ample scope for utilization of those waste materials and producing alternative products.

With the modern population living standards and maintaining a costly lifestyle, the transport from one place to others are comparatively easier than in the olden days. The number of vehicles used by the people is tremendously increasing day by day and of course, the worn-out tyres as well. On a global scale, the worn-out tyres create severe environmental hazards due to their nature of non-biodegradable. Every year almost 1000 million tires are disposed of, and 50% of them are not recycled. In 2030, the annual accumulation of tires will reach 1200 million. In hot climate regions, the tyres create a fire hazard as well reported (Girskas & Nagrockienė, 2017). The developed countries all over the world are following a line of investigation, the way to reprocess the worn-out tyres other than landfilling and put in the ground, which creates serious health issues. A more environmentally sustainable solution for scrap tyre waste management is needed.

A possible solution relates to the use of tyre rubber waste is as an aggregate replacement in construction products. Mechanical grinding generates chipped rubber to replace coarse aggregates. Cryogenic grinding usually produces crumb rubber (CR) to replace fine aggregates (Azevedo, Pacheco-Torgal, Jesus, Barroso De Aguiar, & Camões, 2012). Researchers have been utilizing the tyre aggregate in precast building products such as hollow blocks and bricks due to its bending and cracking shrinkage resistance when compared to conventional units (Aattache, Mahi, Soltani, Mouli, & Benosman, 2013; Corinaldesi, Mazzoli, & Moriconi, 2011; Sienkiewicz, Kucinska-Lipka, Janik, & Balas, 2012; Sodupe-Ortega, Fraile-Garcia, Ferreiro-Cabello, & Sanz-Garcia, 2016). Although it has advantages, still there is no standardization of final properties and durability are reported and approved as on date, and it creates difficulties in commercializing these products (Ling, 2012; Silva, De Brito, & Dhir, 2014; Turgut & Yesilata, 2008).

The exploitation of industrial wastes and by-products is a significant threat faced today due to the disposal cost and potential pollution problem associated with it (Gorai B, 2003; Ramaiah Prakash, Thenmozhi, Raman, Subramanian, & Divyah, 2021). One of the most potential alternate fine aggregate replacements derived from the copper extraction process is copper slag. As per the reports, it was noted that the production of one ton of copper yields around 2.2 tons of slag is generated (Chithra, Senthil Kumar, & Chinnaraju, 2016). In the present scenario, the worldwide production of Copper Slag (CS) is 40 million tonnes and if it has been adequately used will be a sustainable substitute for tremendous demand for natural aggregate worldwide (Prem, Verma, & Ambily, 2018). Slags have cementitious or pozzolanic properties which trigger the researchers to use them in cement or concrete. Copper slag is a by-product derived during the matte smelting and refining of copper. Copper slag is generated when copper extraction is done by smelting from its ore. Generally, impurities floating on the molten metal during smelting are removed and quenched in a large volume of water resulting in the formation of angular granules called copper slag (Mohammed, Anwar Hossain, Eng Swee, Wong, & Abdullahi, 2012).

Fly ash bricks are the latest advancement in the history of bricks as they can be produced without firing, and hence the energy emission is reduced. The usage of fly ash bricks is having tremendous advantages over clay bricks as it depletes the earth's topsoil and further pave the way to degrade the land. The properties of the mixture produced fly ash lime gypsum (Fal-G) bricks act as a 'hydraulic cement' and it behaves similar to cement as in the presence of water it sets and getting harder and stronger with the age of curing and it does not need a sintering process. It is estimated that 200 tonnes of coal are essential to sinter one million clay bricks, a process that liberates over 180 tonnes of carbon dioxide. The production process of fly ash-lime- gypsum bricks eliminate this process and has the potential to earn carbon credits in return (Y. Singh, 2017). A large amount of stone dust is produced during the production of aggregates while in the crushing operation of rocks in rubble crusher units. It may create environmental pollution if not utilized properly. Hence in this attempt, stone dust is utilized in different combinations with crumb rubber and copper slag to manufacture bricks. For more extensive production and application of waste -added brick further research and development are needed (Monteiro & Vieira, 2014).

The novelty of this investigation is to use sparingly the existing resources such as natural sand and besides avoiding the solid waste disposal of worn tyres and copper slag sustainably seeks to assess the effects to utilize these wastes in a most popular construction material such as brick. It was noted that most of the research carried out with the copper slag and crumb rubber are within cement and concrete products. Still, there is a necessity that the effect of copper slag and crumb rubber with the fly ash in precast brick products and is not explored as on the best knowledge of authors.

In the current investigation, an attempt is made to incorporate the rubber after the cryogenic process and air-cooled slag as an aggregate in partial replacement of stone dust in ash bricks. The experimental program consisted of the characterization of crumb rubber and copper slag which includes the chemical analysis, scanning electron microscopy (SEM) and pore size distribution. The mechanical and durability properties were determined with different stone dust replacement dosages of crumb rubber and copper slag. The result of this program shows that the copper slag-based bricks perform better when compared to rubber-based bricks and it satisfies the minimum requirements stipulated as per Indian codal specifications. These results may lead to the successful utilization of these abundant waste materials in brick products.

2. Materials and methods

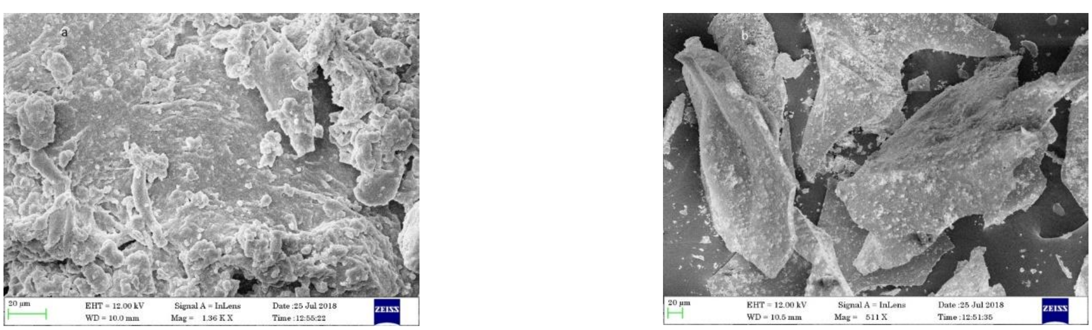
2.1. *Raw material characterization and mixture proportions*

The total chemical composition of fly ash used in the present investigation $Sio_2 + Al_2O_3 + Fe_2O_3$ is greater than the stipulated minimum requirement of 70% for class F fly ash as per BIS 3812 and ASTM C 618 ('ASTM 2015') class F pozzolan. As-received stone dust from the local quarry (Coimbatore, Tamil Nadu, India) is utilized for the study after sundry for 24 hours. The fineness modulus of stone dust was 1.42 with a specific gravity of 2.5. Stone dust was having a water absorption of 6.1%.

Table 1. General chemical composition of crumb rubber and copper slag.

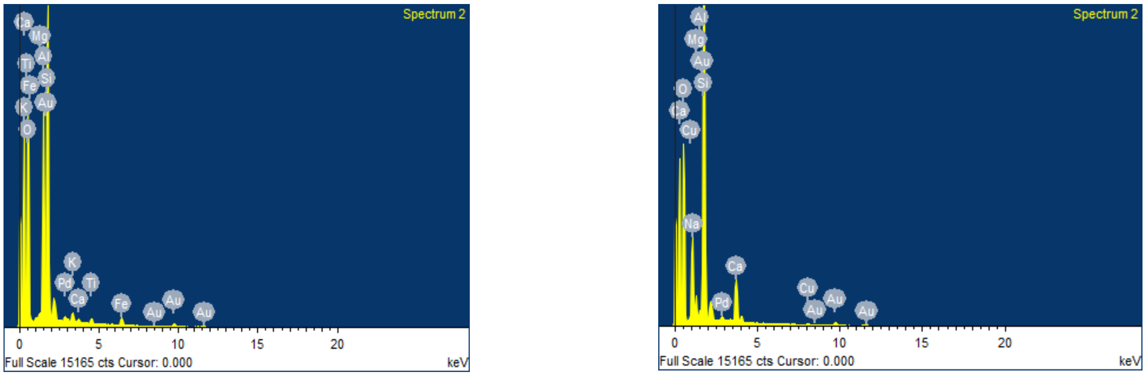
Material	SiO_2	Na_2O	MgO	Al_2O_3	SO_3	Cl	K_2O	CaO	Fe_2O_3	Pd L	Au M
CS	45.36	1.03	0.67	1.8	0.85	0.23	0.83	4.66	37.23	-	4.26
CR	34.95	-	1.34	0.98	6.79	3.94	0.27	14.17	1.43	4.86	18.29

Crumb rubber 20 mesh size (1 mm) obtained from the southern part of Tamil Nadu (Paramakudi, Tamil Nadu, India) were used for the study. The specific gravity of crumb rubber was 1.09 and the fineness modulus was 2.9. Sieve analysis of rubber done as per ASTM C33-01(ASTM C33-01, 2002) and satisfy the limits. Locally sourced hydrated lime (Coimbatore, Tamil Nadu) was used for the study. Copper slag obtained from Tuticorin, Tamil Nadu, India. The fineness modulus of copper slag was 3.3 and the water absorption was 0.29 % with the specific gravity of 3.9. The chemical properties of CS and CR are presented in Table.1. Copper slag contains more silica and ferrous composition whereas the rubber contains higher silica content than other chemical contents. The SEM micrograph and EDS of the CR and CS particles are shown in Fig.1a. & Fig.1b., and Fig.2a. & Fig.2b respectively. The morphology of rubber aggregates has a smooth surface whereas the slag aggregate displays an irregular shape morphology.



(a) (b)

Figure 1. (a) micrograph of rubber aggregate; (b) micrograph of slag aggregate.



(a) (b)

Figure 2. (a) EDS of rubber aggregate; (b) EDS of copper slag aggregate.

The quality of bricks very much depends on the pore size distribution of the ingredients. By engaging BET analysis, the surface area and pore size distributions are evaluated. Based on the observation the pore size of ingredients falls between 2-50 nm and hence in the case of mesoporous the pore size distribution has arrived based on the BJH method. The adsorption/desorption and BJH plots are provided in Fig.3. The surface area, total pore volume and mean pore diameter of the ingredients are presented in Table.2. It is observed that comparatively the specific surface area and pore volume are less in the case of rubber aggregates. Though the total pore volume is less in copper slag aggregates, the surface area is higher due to the rough surface texture of copper slag aggregates that is evident from microscopic observation. The mean pore diameter of both the slag and rubber aggregates are having nearly the same values as per the observation.

Table 2. Pore size distribution and BET surface area of ingredients.

Ingredients	Area, as, BET(m^2/g)	Total Pore Volume(cm^3/g)	Mean Pore Diameter(nm)
Fly ash	1.843	0.0023154	5.02
Stone dust	0.130	0.0073217	6.61
Copper slag	0.168	0.00016745	3.97
Crumb rubber	0.019	0.000019019	3.91

Before starting the production of bricks, several series of compression tests were performed for target compression strength of 5 MPa. Mix proportions proposed for the study are presented in Table 3. The mixes were named as 5CS,10CS,15CS, 20CS, 25CS and 5CR,10CR,15CR, 20CR and 25CR for slag and rubber aggregate replaced bricks where the prefix in each mix shows the percentage replacement of stone dust in the brick mix. The volume of stone dust is fixed as 25% of the weight of a brick. The mix 25CS and 25CR denote the complete replacement of copper slag and crumb rubber in the brick mix. Crumb rubber and copper slag were used as a partial substitute with stone dust by weight. The replacement levels were 0%, 5% ,10%, 15%, 20% and 25%. Table. 3 presents the mix composition of mixes in percentage per kg of brick production. Ordinary drinking water without any treatment was added to make the brick mixes. Water pH value was 7.9 with water conditioned at 22 +/- 3° C was used in plant trials. The water was used as per the practical guidelines set out in the long-term industry production needs. The lime and gypsum kept constant for all the mixes as 12% and 3% respectively. Besides, copper slag and crumb rubber were mixed in two different percentages 5%, and 10% in combination and replaced with stone dust and the bricks were produced.

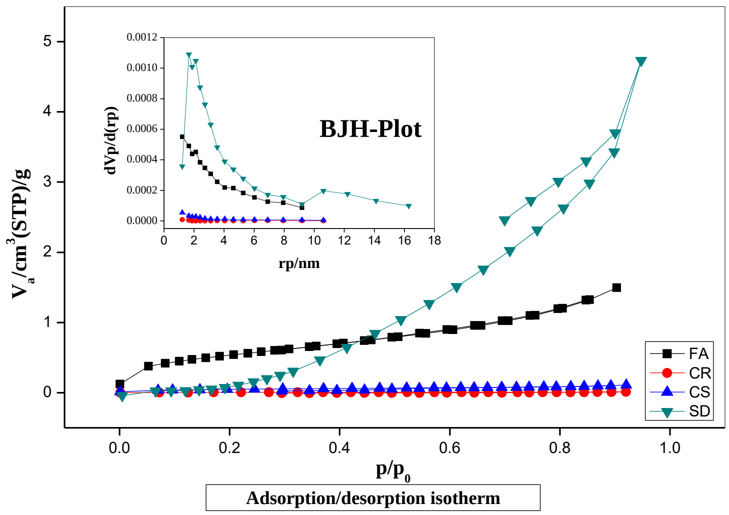


Figure 3. BJH -plot and adsorption/desorption isotherm of ingredients.

Table.3 Mix proportions for rubber aggregate brick and slag aggregate brick.

No	Brick types	Various ingredients in percentage (%)					
		FA	Lime	Gypsum	SD	CS	CR
1	Conventional	60	12	3	25	-	-
2	5CS	60	12	3	20	5	-
3	10CS	60	12	3	15	10	-
4	15CS	60	12	3	10	15	-
5	20CS	60	12	3	5	20	-
6	25CS	60	12	3	-	25	-
7	5CR5	60	12	3	20	-	5
8	10CR	60	12	3	15	-	10
9	15CR	60	12	3	10	-	15
10	20CR	60	12	3	5	-	20
11	25CR	60	12	3	-	-	25
12	5CS5CR	60	12	3	15	5	5
13	10CS10CR	60	12	3	5	10	10

SD-stone dust; CS-copper slag-CR-crumb rubber

2.2 *Production of bricks*

A total of 650 bricks consisting of 13 brick types of size 230mm x 110mm x 75 mm were cast in the factory-controlled environment by keeping the lime binder and gypsum constant except for aggregate constituents. Each batch was mixed in a power-driven revolving pan mixer. The lime and gypsum are pre-mixed for 2 minutes in the pan mixer, and the mix was intimately done without lumps with a fixed quantity of water. Then stone dust and fly ash were added to the pan mixer with an additional quantity of water together with crumb rubber or copper slag, and the mixing was done till it gets a homogeneous mix. Then the ingredients are transported to fill the mold via a conveyor belt, and the semi-dry pressure of 150-200 kg/cm^2 was applied. The bricks were then taken out and stacked as per the brick types and kept for four days under a covered roof curing with a temperature of 23+/- 4° C. Following this process, the products were transported to curing facilities and were water sprinkle cured for 21 days before obtaining a final product dry-cured for three days.

2.3 *Test methods*

Mechanical properties of brick specimens were done as per ASTM C67 (ASTM C67, 2002) (Standard test methods for sampling and testing brick and structural clay tile). Five specimens were tested for each mix proportion. At first, the unit weight of brick specimens was determined. For 24 hours, brick specimens were oven-dried at 100 °C and then cooled for 5 hours at room temperature (25°C). Afterwards, the weight of brick specimens was determined using a weighing balance of 0.50 g least count. The compressive strength was determined by keeping the specimen under steel plates on top and bottom in a compression testing machine of capacity 300 T. The split tensile strength was determined as per ASTM C1006-07 (ASTM C1006, 2007) flexure test was performed as per ASTM C67, and the load was applied in the middle of the brick specimen using a flat loading plate in the direction of brick depth. The displacement rate was 1.25 mm/min. The span of tested brick specimens was 200 mm. The microstructural analysis of copper slag and crumb rubber samples, optimum CR and CS bricks at the age of 28-days were analyzed by using SEM (Zeiss Sigma VP-FE-SEM). Medium size particles are selected randomly and were sputtered with gold-palladium (4nm size approx.) before SEM examination. UPV tests were also performed on brick specimens as per ASTM C597-16.

3. Experimental results and analysis

3.1 *Influence of CS and CR on physical and aesthetic properties*

The density plays a vital role in deciding the strength properties of the bricks. Fig.4 shows the hardened density of bricks incorporating CS and CR aggregates and their combined substitution. It shows that the substitution of crumb rubber tends to decrease the density. The dry density of rubber aggregate bricks ranged from 1471 to 1557 kg/m^3 based on the crumb rubber varying substitution whereas the control bricks were having a density of 1663 kg/m^3. Maximum density reduction was around 12 % in regards to conventional brick mix. This is due to the low specific gravity of crumb rubber (1.09) than the fine aggregate (2.5). This weight reduction is in satisfactory agreement with earlier reports by the researchers (Mohammed et al., 2012; Sodupe-Ortega et al., 2016). Also, the reason attributed to the reduction in density is due to the enormous absorption of air molecules generated during the mixing process (Turatsinze, Bonnet, & Granju, 2005).

The increase in the substitution of copper slag increases the dry density of slag aggregate bricks. It is noted that almost all the substitution levels of copper slag improve the dry density of slag aggregate bricks. Since the specific gravity of copper slag is higher, it improves the dry density of the bricks. Also, the other reason for this increase in density is due to the inherent higher percentage of Fe2O3 and the better interlocking of the ingredients. Also, the air-cooled copper slags are comparatively denser and have a crystalline structure, not like quenched copper slag which has a more porous and granulated texture. The results of published literature reassure this. The maximum improvement in density occurs in 25% replacement of around 4.5% than the control mix. The improvement in dry density percentages is not appreciable as it shows 1.4%, 3%, 3.48%, 3.95%, 4.5% for the substitution of 5-25% of stone dust. The fineness of particles and individual size distribution is the primary significance in the production of bricks. The fineness of particles ensures bricks with better surface quality and provides a great aesthetic appearance (Santhakumar.A. R, 2015). It was noted that the due to comparatively fine particles of crumb rubber provides a smooth surface (Figure 1a) than copper slag (Figure 1b) which provides a rough textured finish to the end products.

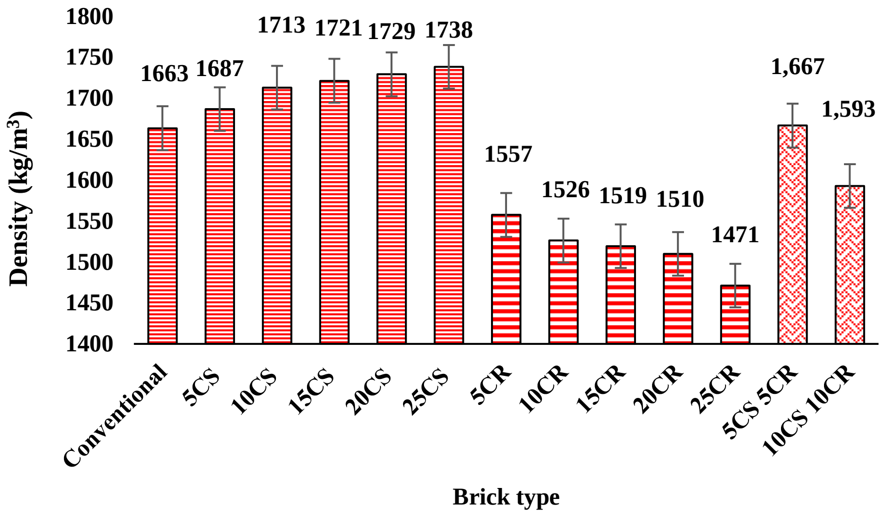
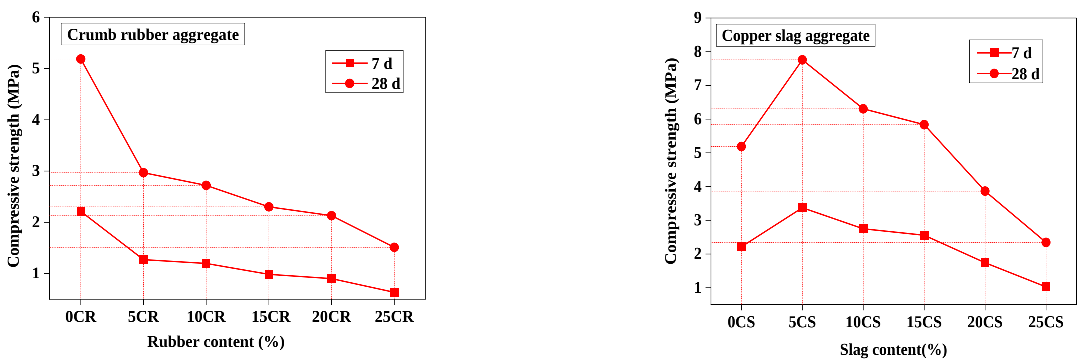


Figure 4. Hardened density of bricks incorporating CR and CS aggregates and its combined substitution.

3.2 *Influence of CS and CR on mechanical properties*

Fig 5. (a) and (b) provide the compressive strength of CR and CS aggregates substituted bricks respectively.

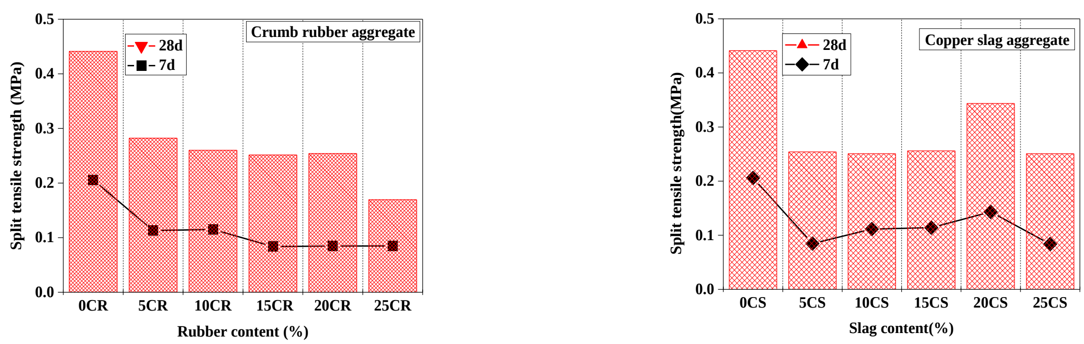


(a) (b)

Figure 5. Compressive strength (a) CR aggregate bricks (b) CS aggregate bricks.

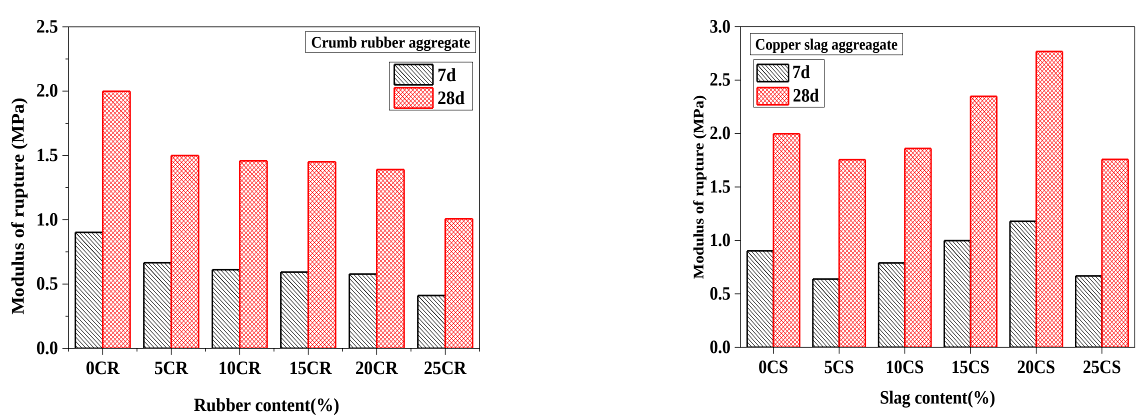
It is to note that the CR bricks show a declining trend of compressive strength by the increased substitution of rubber aggregate at both the ages of 7 and 28 days observed. The compressive strength was directly proportional to rubber aggregate substitution (S. B. Singh & Munjal, 2017; Sodupe-Ortega et al., 2016; Vladimir, G, Haach, Graça, V, Paulo, 2013). The reason for the reduction in strength may be due to the softness of the rubber particles that may not properly bond with the aggregates (Sienkiewicz et al., 2012). The low stiffness of rubber particles is also the deciding factor of compressive strength reduction. It is to be noted that the percentage reduction in strength at the 28 days is 43%, 48%, 56%, 59% and 71% for the 5-25% substitution of crumb rubber in the bricks. Also, the reduction in strength when compared to 5% substitution for other replacement levels are 8-49% observed for 10-25% replacement. The 7 days' strength of bricks, when compared to the 28 days' strength in the tune of 42-43%, are observed. The slag ash bricks show the higher compressive strength at the addition of 5% slag and then it shows in decline trend after the addition of slags. Up to the addition of 15% of CS, the strength values are comparable with the control mix, and then the values are reduced than the control bricks. When compared to control at the age of 28 days, the 5-15% substitution of slag provides an increase in strength at the tune of 50%, 22% and 13%. The addition of 20 and 25% Slag provides a reduction in strength of 26% and 55% at the age of 28 days. Both the ages of 7 and 28 days shows a similar trend for all the combinations.

Commonly the tensile strength of the brick and brick masonry are neglected presuming these values are negligible. However, in particular occasions, it is essential to consider especially in place of to avoid the provision of RC bands or reinforcements, and in corrosion-prone zones, like the marine environment and splash zones (Santhakumar.A. R, 2015). For brittle materials like masonry units, it is difficult to examine the tensile strength by direct tests. Hence modulus of rupture or split tensile strength is used for this purpose. The split tensile strength of rubber aggregate bricks is in the range of 0.17-0.282 MPa. All the substitution levels of rubber drastically reduce the strength. The reduction in strength for 5-25% of crumb rubber from 36-62% when compared to the conventional mix. CS aggregate substituted bricks show the split tensile strength of 0.48 - 0.139 MPa. The 5% replacement of slag provides an increase in strength than that of control bricks, and all other replacement level shows lesser strength than the control brick mix. The 7 days' strength are 33-65 % than that of 28 days are reported in all replacement levels for slag aggregate bricks. Fig.6 a & b show the split tensile strength of CR and CS aggregate bricks respectively.



(a) (b)
Figure 6. Split tensile strength (a) CR aggregate bricks (b) CS aggregate bricks.

The rupture modulus of CR aggregate bricks is showing the same trend as that of compression and tensile strength. The increased substitution of crumb rubber drastically reduces the rupture modulus. Fig.7a and 7b show the rupture modulus of CR and CS aggregate substituted brick samples. The replacement level of 25% of crumb rubber reduces the rupture modulus by exactly half that of the control brick mix. The 5-20% substitution reduces the strength as 25%, 27%, 27%, and 50% respectively at the age of 28 days.



(a) (b)
Figure 7. Rupture modulus (a) CR aggregate bricks (b) CS aggregate bricks.

Up to 15%, copper slag substitution shows improved strength than the control mix at the age of 28 days. The maximum strength gains of 46% was obtained in 5% substitution of slag.Fig.8 provides the percentage variation of mechanical properties with the conventional brick mix at the ages of 28 days.

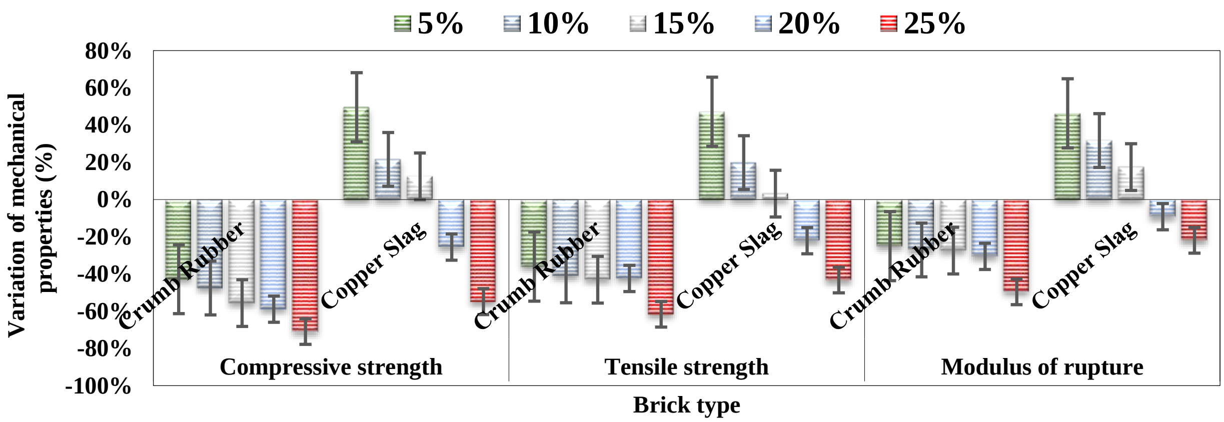


Figure 8. Percentage variation of mechanical properties with the conventional brick mix at the age of 28 days.

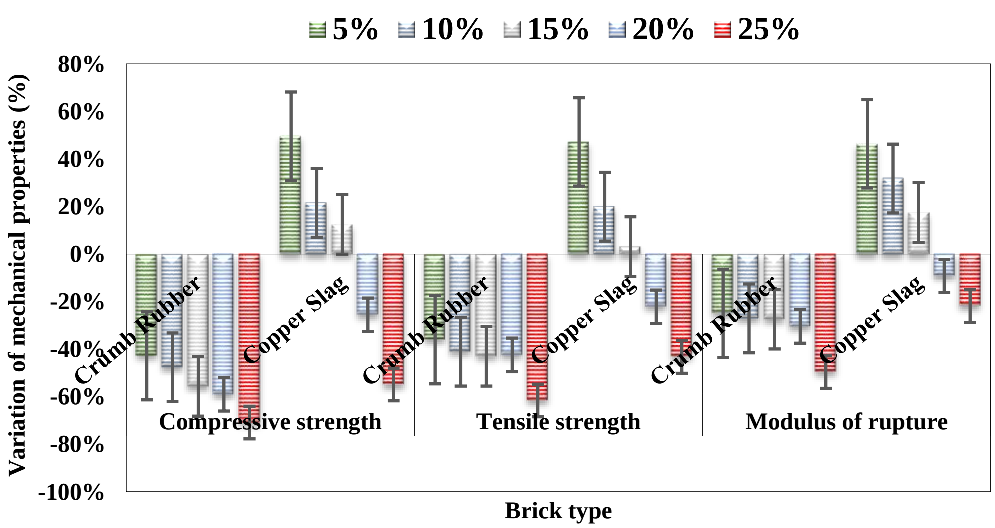


Figure 9. Percentage variation of mechanical properties with the conventional brick mix at the age of 28 days.

Incorporation of 5% of CS and CR provides 50% and enhanced and 43% reduction in compressive strength. Similar way, the split tensile strength of 5% of CS and CR shows 47% enhanced strength and 26% reduction in strength when compared to the conventional mix. The compressive strength of crumb rubber increases to a greater extent if the substitution percentage gets increased. The main reason for the enhancement in water absorption of crumb rubber is the presence of air in the CR microstructures. The air content increases as the percentage of CR replacement to fine aggregate increases. This is because CR repels water during mixing and thereby allows entrapped air on the surface of CR particles. Upon hardening, voids are formed inside the CR mixture (Mohammed et al., 2012). Fig. 9 and Fig.10 provides the mechanical properties and percentage variation regarding conventional mix for the combined substitution of CS and CR aggregates.

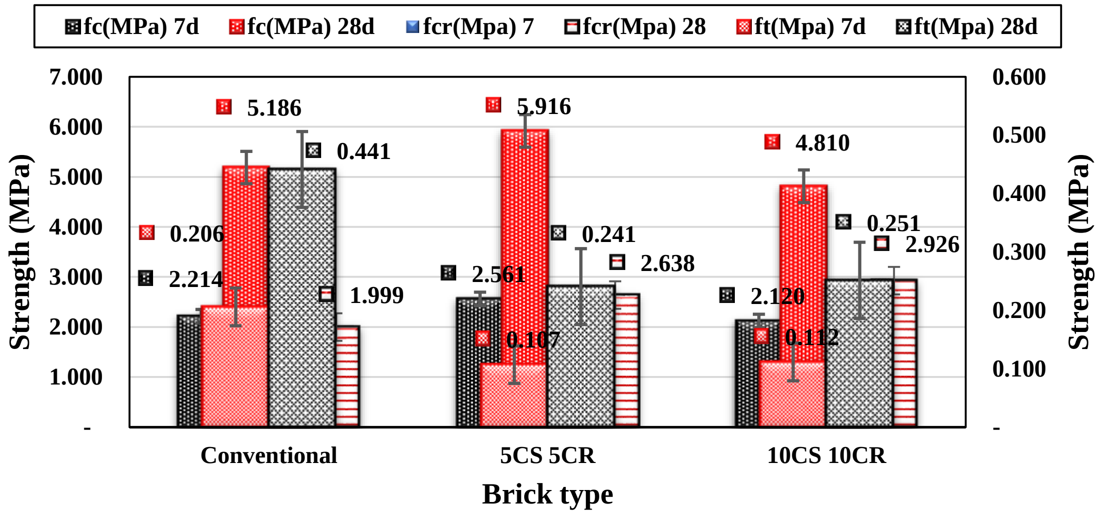


Figure 10. Mechanical properties of combined substitution of CS and CR aggregates.

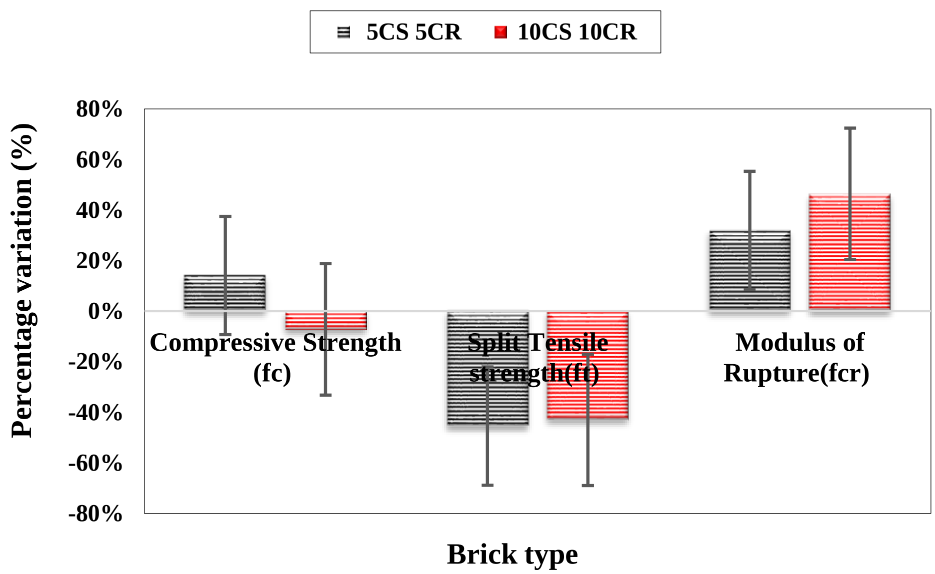


Figure 11. Percentage variation of mechanical properties with the conventional brick mix for the combined substitution of CS and CR at the age of 28 days.

The incorporation of 5% of CS and 5% of CR shows comparatively higher strength. The split tensile strength of both the incorporation of CS and CR aggregates provides reduced strength when compared to the conventional mix. The modulus of rupture gets increased due to the combined addition of CS and CR aggregates. With the substitution of CR aggregates, the strength properties were reduced due to its loose matrix as evident from microscopic examinations. It is observed that 14% and 46% increased compressive strength and modulus of rupture is observed for the combined substitution of 5CS5CR and 10CS10CR respectively.

3.3 *Influence of CS and CR on direct UPV measurements*

Usage of UPV test is the fast and economic non-destructive test for the evaluation of the quality of brick (Kazmi, Abbas, Nehdi, Saleem, & Munir, 2017). Test results of the UPV for the brick samples incorporating crumb rubber and copper slag are provided in Fig.11.

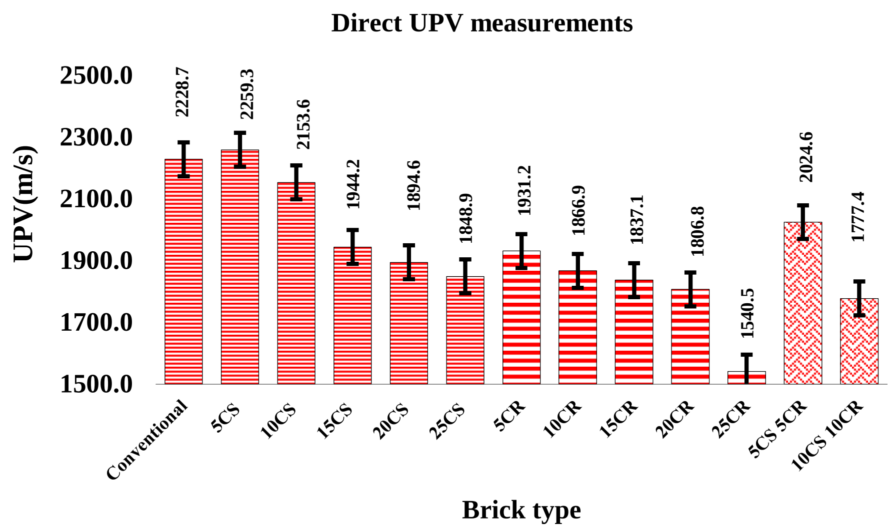


Figure 12. UPV measurements of brick specimens.

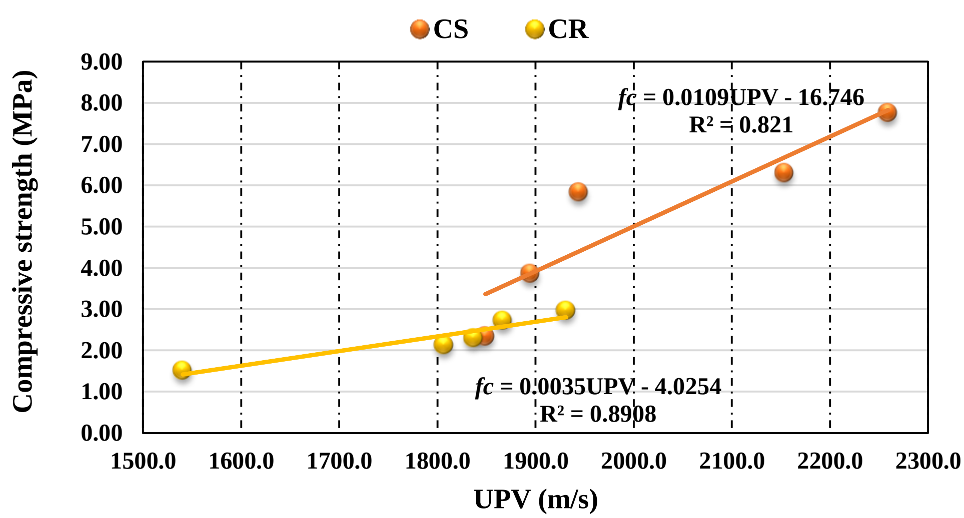


Figure 13. Correlation of UPV and compressive strength of CR and CS aggregate bricks.

It is observed that the increased substitution of CS and CR tends to reduce the UPV Values significantly. For instance, the UPV decreased from 2228.7 m/s to 1848.9 m/s and 1540.5 m/s in the case of CS and CR incorporation respectively. The addition of up to 10% of CS provides the UPV values greater than 2000 m/s. The combined addition of CS and CR of 5% shows UPV of 2024 m/s. The addition of CR shows the UPV values in the range of 1931.2 m/s to 1540.5 m/s whereas the incorporation of CS shows the UPV in the range of 2259.3 m/s to 1848.9 m/s. It is also noted that the observed UPV values were consistent with the compressive strength values. Fig.12 shows the correlation of compressive strength and UPV values of CS and CR added brick samples. Based on the earlier study (Koroth, Fazio, & Feldman, 1998)the UPV of less than 1000 m/s indicates less durable and of value greater than 3000 m/s indicates durable bricks. The result of the current study shows the observed UPV values in the range of 1541 m/s to 2259 m/s. The bricks can be used for moderate weathering exposure conditions and the ASTM C67 (ASTM 2002) standard procedures were used to determine the performance of the bricks.

3.4 *Influence of CS and CR on microstructural properties*

3.4.1 *Fourier Transform Infrared Spectroscopy*

Fig.13 provides the Fourier Transform spectroscopy of basic ingredients and the three types of developed bricks such as conventional, optimum CS and CR aggregate incorporated bricks. It is noted that the peaks that appeared at 3679 cm^{-1} are attributed to the OH-bonding from $Ca(OH)_2$. The peak at 3400 cm^{-1} is due to the symmetric stretching vibration of water molecules present in the hydrated products.

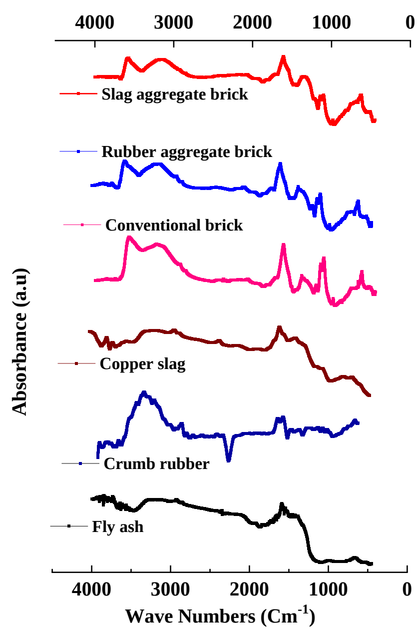


Figure 14. FTIR spectra of raw materials and bricks.

The bands of 1100-600 cm^{-1} are attributed to Si-O and Al-O Asymmetric stretching vibrations and it can be evident from the peaks at 1127 cm^{-1} and 1173 cm^{-1}. The bands at 997/999/998.25 at conventional, CS and CR incorporated bricks shows the strong Si-O-Si Asymmetric Stretching Vibrations.C=O, stretching vibrations at 1865.5 observed are the characteristic bands of CO_3.

3.4.2 *Microscopic examination*

The microstructure of CS and CR bricks can be seen from the micrographs taken using a scanning electron microscope (SEM). Fig 14 shows the SEM micrographs of the crumb rubber aggregate incorporated bricks.

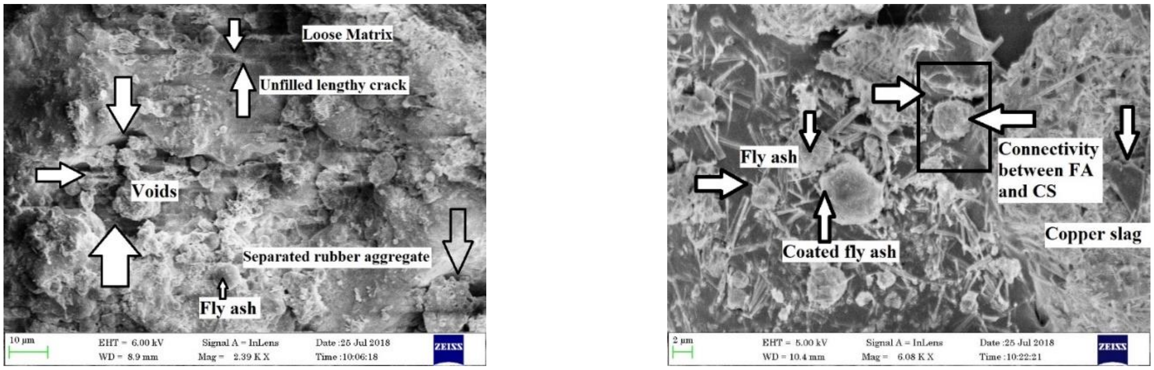


Figure 15. FESEM micrographs of 5% Crumb rubber aggregate incorporated bricks.

Crumb rubber particles are having spongy morphology whereas the slag particles have dense pack up with very sharp edges. Scanning electron microscopy analysis confirms that the porous microstructure of brick specimens incorporated with crumb rubber leads to lesser unit weight leading to lighter structure. It was noted that the unfilled lengthy cracks are identified as shown in Fig.14.

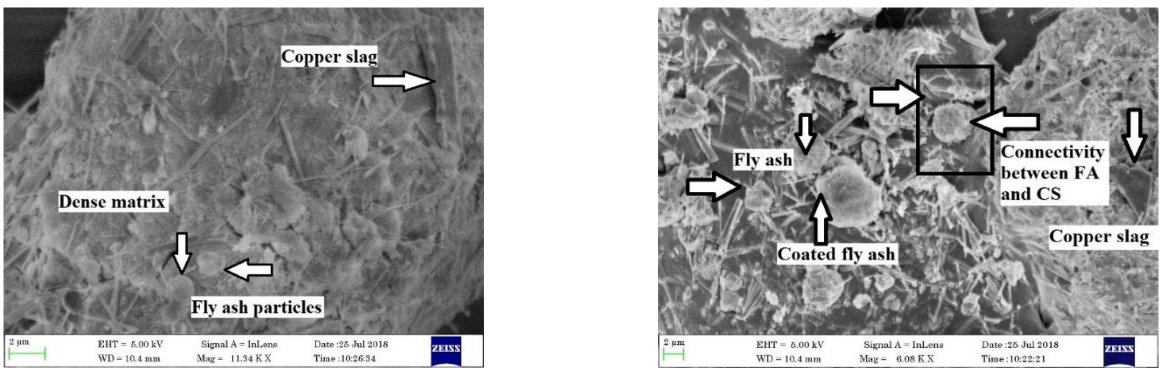


Figure 16. FESEM micrographs of 5% Copper slag aggregate incorporated bricks.

The rubber particles are separated from the matrix and lead to voids formation. During the loading, these voids lead to failure even at a lower magnitude of application of load. Crumb rubber-based bricks show a more porous structure than copper slag bricks. These pores were considered regions of weakness and resulted in strength reduction in rubber aggregate bricks. In contrast, the pores are less and a comparatively dense-packed matrix was noted in the case of slag added bricks. The C-S-H gel coated on the copper slag can be visible from Fig 15. The application of compressive pressure, which strengthens the materials may explain the grain boundaries due to interface reactions. This mechanism led to the densification of the mass and reduced the porosity and may improved the mechanical properties of slag added bricks. Comparatively copper slag bricks show dense backup due to the incorporation of copper slag. Fly ash and copper slag particles are not having proper bondage at some places, which leads to diminishing the strength enhancement. The results are in harmony with the mechanical studies.

4. Conclusions and comments

The utilization of crumb rubber and copper slag aggregates as partial substitution in industrial brick production has been the objective of this investigation. Waste rubber causes a considerable amount of environmental degradation. Disposal of copper slag is the point of concern in terms of solid waste management point of view. Reusing and recycling these wastes as partial substitution in the production of industrial brick surely has a significant contribution to the economy and the environment by reducing the ill effects that arise from the accumulated rubber debris and copper slag. Based on the results of this current investigation, the following conclusions can be drawn;

1. In general, the incorporation of copper slag provides a rough textured finish of bricks, and the addition of crumb rubber provides a very smooth texture finish of bricks.
2. The BET surface area of stone dust, copper slag, and crumb rubber are reported as 0.13,0.16 and 0.019 m^2/g. It reveals that the copper slag has more surface area than crumb rubber and the possible availability of active sites are higher, hence the chance of bonding is higher in the case of slag aggregate bricks than rubber aggregate bricks.
3. The mean pore diameter of copper slag and crumb rubber is reported as 3.97 and 3.91 nm. Although both the materials are having almost the same pore diameter, which is not reflected in density and strength characteristics as copper slag provides a comparatively denser matrix than crumb rubber. Correspondingly the pore volume reported in the study reveals that the copper slag particles are having more pore volume than the crumb rubber particles.
4. Copper slag and crumb rubber both provide the opposite trend in regards to the density characteristics of copper slag and crumb rubber bricks. The addition of crumb rubber reduces the density gradually as it can observe from scanning electron microscopy study that the crumb rubber brick shows porous structure. A maximum density reduction of 12% than the control brick type was observed. The addition of slag improves the density of copper slag added bricks and the maximum improvement of 4.5 % is noted.
5. It was observed that the addition of crumb rubber drastically reduces the strength characteristics of CR added bricks. The upper and lower limits of compressive strength reduction occur at 25% and 5% substitution level of 71%, and 43% than the control was noted.
6. The substitution of 5% copper slag is the optimum as it shows enhanced strength. Up to 15% substitution provides better strength than other replacement levels, and further addition of copper slag reduces the strength in slag added bricks than control is observed.

In conclusion, with the increasing demands of the construction industry on the date, the brick quality and economy are the utmost criteria to consider. This investigation has a significant role in the recycling of waste materials in brick production with a significant contribution to the environment. The results obtained in the present investigation reveal that the addition of copper slag in bricks is providing better results than the crumb rubber added bricks. It is suggested to improvise the production of slag bricks as it has the advantages of reusing the potential copper slag as the fine aggregate replacement in the industrial brick.

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