



# Comparing Crushed Brick as Coarse Aggregate Substitute in Concrete: Experimental vs. Numerical Study

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## Abstract

As building construction speeds up, demolitions will increase due to concrete's limited lifespan ultimately ending in demolition. In earthquake-prone countries like Nepal, buildings may collapse during earthquakes, leading to the disposal of bricks creating potential environmental pollution. This research explores the use of Crushed Brick Aggregate (CBA), obtained as a replacement for Natural Coarse Aggregate (NCA) in concrete. Laboratory tests of concrete underwent compressive and tensile strength tests, while the aggregate underwent sieve analysis, impact, abrasion, and water absorption tests. Similarly, cement was subjected to tests for w/c ratio, setting time, and consistency. Employing ABAQUS software for numerical modeling, an analysis of how the concrete responds to various pressures has also been conducted. Substituting NCA with CBA at 10%, 15%, 20%, and 25% by weights, the study finds that up to 20% replacement maintains comparable strength, offering potential application in construction. The research emphasizes reusing bricks in construction instead of discarding them, which reduces waste and enhances resource recycling and conservation, ultimately promoting global sustainability. This encourages engineers, and researchers to develop eco-friendly concrete using recycled materials. The limitations encompass durability concerns, water absorption, and project cost. Furthermore, researchers may investigate how the chemical composition of bricks affects concrete strength.

**Keywords** Natural Coarse Aggregate (NCA) · Crushed Brick Aggregate (CBA) · Concrete · Environment · Waste management · Recycled brick · Demolition building

## 1 Introduction

In today's world, where sustainability is at the forefront of construction practices, there is a growing interest in finding alternative materials for making concrete. One such material that has garnered attention is crushed brick aggregate. This material shows promise as a potential replacement for natural aggregate in concrete mixtures. The primary goal in construction is to build structures that are durable and long-lasting, especially considering the limited lifespan of buildings and the ever-present risk of natural disasters such as earthquakes. In this context, utilizing recycled materials like crushed brick aggregate emerges as a compelling solution. Not only does recycling construction waste

address environmental concerns, but it also helps conserve valuable natural resources, aligning with the principles of sustainable development. Limited studies have investigated the environmental and economic implications of utilizing crushed brick aggregate in concrete mixtures. Assessing the life cycle environmental impacts and cost-effectiveness of incorporating crushed brick aggregate can provide valuable information for decision-makers in the construction industry. Furthermore, there is a deficiency in software simulations analyzing stress distribution and crack patterns in concrete containing crushed brick aggregate.

The primary objective of this research is to investigate the feasibility and effectiveness of utilizing crushed brick aggregate as a partial or complete replacement for natural aggregate in concrete mixtures. Through comprehensive analysis, the study aims to assess its impact on mechanical properties, durability, and overall performance of concrete. By addressing these objectives, this research seeks to contribute to sustainable construction practices by promoting

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the recycling of construction waste and conserving natural resources.

Nepal is situated in a region prone to earthquakes, and the devastating earthquake of 2015 resulted in over 600,000 structures being damaged or demolished, according to data from the Nepal government. Many of these structures predominantly utilized brick materials. The aftermath of such disasters often sees the disposal of demolished materials, including concrete and bricks, into landfill sites or indiscriminate dumping, leading to environmental pollution. Moreover, the finite lifespan of concrete structures necessitates eventual demolition, exacerbating environmental concerns. Utilizing crushed bricks presents challenges in this context. Hence, this study was undertaken to address these issues.

In this study, crushed brick aggregate was incorporated as a partial substitute for natural aggregate in the concrete mix. The bricks were crushed into pieces smaller than 20 mm and sieved before being added to the concrete mixture. To enhance the ease of mixing and workability, additional water was introduced to allow the dry brick aggregate to absorb moisture. Replacement levels of 0%, 10%, 15%, 20%, and 25% of the natural coarse aggregate by weight were investigated and denoted as R0, R10, R15, R20, and R25 respectively.

Using Crushed Brick Aggregate (CBA) as a replacement for Natural Coarse Aggregate (NCA) in concrete poses some potential limitations and challenges. These include variability in properties such as shape and size, increased water absorption leading to potential impacts on workability and strength, susceptibility to alkali-silica reaction (ASR), potential compromises in durability due to weathering, color variation concerns, environmental considerations regarding embodied energy, and fluctuations in availability and cost. Addressing these challenges requires careful consideration in concrete mix design, quality control, and construction practices to ensure satisfactory performance and durability of CBA-incorporated concrete.

The construction sector is an inefficient industry that results in socio-environmental problems primarily due to treating the outcome as a throwaway product that is poorly recyclable (van den Berg 2019). Currently, brick is considered as one of the most sought materials in the construction industry (Murmu and Patel 2018; B100-68-RiseFallCladdings.pdf) only behind concrete (Shrapnel 2006). To preserve the natural supply of aggregate as well as to reduce waste and storage for the waste, recycling of crushed bricks as the coarse aggregate is an interesting concept (Adamson et al. 2015).

Even with the benefits of using recycled elements in construction, the actual use of said elements should follow a codified set of rules. Further, the economic benefits associated with the recycling of construction materials

should be thoroughly assessed. These benefits can be in the form of raw material savings, lower energy costs, and shorter construction time. Moreover, the sourcing of the said materials should be so that it minimizes the negative impact on the environment (Rybak-Niedziółka et al. 2023). Further, mainstream adoption of recycling of demolished materials suffers from a poor image linked with recycling activities, lack of confidence in the final product, lack of recycling facilities, lack of government support, lack of awareness and absence of required technology, and the low dumping cost in developing countries (Rao et al. 2007).

Sandanayake et al. performed a bibliometric assessment of 1465 research publications and found that most of the research in concrete sustainability has been done on the topic of replacement of fly ash, and recycled aggregate is the most researched material which is used by replacing cement and aggregates. It was observed that most research focused on the experimental testing of mechanical and durability properties and the sustainable performance of concrete was rarely analyzed (Sandanayake et al. 2020). One author noted that, If conventional coarse aggregate is replaced by recycled concrete aggregate, the best percentage of replacement is 30% in terms of mechanical properties (Limbachiya et al. 2011).

In general, use of recycled aggregates lowers the compressive strength of the concrete. The exception to this was found in concrete composed of recycled fine aggregate from brick ceramic (RFB). Further, the concrete's modulus of elasticity decreased for all types of recycled aggregates (Cabral et al. 2010). A study analyzed concrete's performance in the context of physical, mechanical properties and environmental sustainability. It was observed that, fine aggregates have the greatest number of alternatives and replacement level (Collivignarelli et al. 2020).

Cavalline and Weggel replaced traditional coarse aggregate with crushed brick obtained from a demolition site to prepare a structural and pavement-grade Portland cement concrete (PCC) mixtures. The study found that the workability of the concrete was adequate and the mechanical properties of the mix was comparable to the traditional mixture of a structural and pavement-grade Portland cement concrete. Furthermore, the research concluded that results for the durability was mixed and further testing was necessary (Cavalline and Weggel 2013). In another study, authors concluded that, in absence of steel, natural coarse aggregates can be replaced by crushed bricks without considerable change in the durability (Adamson et al. 2015).

In a similar study, Debieb and Kenai concluded that, at replacement level of 25% and 50% for coarse and fine aggregates respectively, the characteristics of the resulting concrete is similar to those of natural aggregates concrete or conventional concrete (Debieb and Kenai 2008).

On the other hand, Fořt and Černý used the Life Cycle assessment method to assess the environmental impact of, three potential waste brick recycling scenarios, and found that, despite with the low environmental impact, the application of waste bricks as a recycled aggregate for concrete mixtures, subbase, or road pavement hardly yielded noticeable environmental benefits to CO<sub>2</sub> reduction (Fořt and Černý 2020).

On the usability of such concrete, Gyawali opined that with proper washing, recycled coarse can be used in place of conventional coarse aggregate in the structural concrete (Gyawali 2022). Further, similar research can be found in countries similar to Nepal in the geographical, cultural and development context. A study in Pakistan replaced coarse aggregate with locally available bricks, and obtained a reduced bulk density of 16% as compared to regular concrete (Bhanbhro et al. 2014). Another study in India replaced coarse aggregate with locally available low-strength bricks and obtained a reduced density of 15% (Padmini et al. 2001). A study in Iran concluded that, although the bricks and rocks have considerable difference in compressive strength, the resulting concrete mix produced by using the crushed brick is aggregate has acceptable compressive strength and can be used in non-structural purposes (Bolouri Bazaz and Khayati 2012). Bhanbro et al. further found that there was a reduction in compressive strength of 23.2%, 34% and 37% for 7, 14 and 28 days respectively compared to regular concrete. Further, the dynamic modulus of elasticity of the regular concrete was 29% greater than concrete made up of recycled aggregates (Bhanbhro et al. 2014). High strength concrete can be designed and manufactured by replacing the conventional coarse aggregate with crushed clay brick as long as the brick aggregate is in a saturated surface dry (SSD) moisture condition before the mixing process. Further, it was found that the strength of the bricks is directly related to the strength of the concrete. The higher the strength of the brick, the higher the strength of the concrete (Khalaf and DeVenny 2004).

It was also found that with 100% replacement by RCA the compressive strength decreases by 20–25% than conventional concrete at 28 days, with the same effective w/c ratio (w/c = 0.50) and cement quantity (325 kg of cement/m<sup>3</sup>). This requires high amount of cement to balance the compressive strength thus is not an economic option. On the other hand, it was found that with 25% replacement level, the mechanical properties are the same as that of conventional concrete (Etxeberria et al. 2007). One author noted, that with increasing the replacement level, the saturated density and the mechanical performance of recycled concrete are moderately lower than the reference concrete. Further it was found that, up to 50% replacement level, the concrete made up of recycled aggregate has adequate strength and

durability for housing construction (Medina et al. 2014). Another researcher concluded that, with increase in recycled brick coarse aggregate (RBCA), the cubic compressive strength and elastic modulus of mixed recycled coarse aggregate (MRCA) decreases linearly (Liu et al. 2021).

An artificial neural network (ANN) model was tested as an alternative to conventional lab tests. This model simulated material properties in concrete with crushed brick and roof tile aggregate. From the test, it was seen the ANN model can adequately predict the compressive strength of RBAC when presented with eight input parameters. It was found that aggregate size (fine or coarse) influences the recycled brick aggregate concrete's (RBAC) compressive strength. The drop in compressive strength is significant in coarse aggregate, almost twice as much as fine aggregate. Further, to keep the compressive strength as much as the conventional concrete, the cement percentage in the mix must be up increased by 20% which is directly related to the replacement ratio. It was opined that the additional number of research was necessary in replacement level of 0–50% since most research was conducted by replacing the conventional aggregates by recycled aggregates in percentage level greater than 50% (Kalman Šipoš et al. 2017).

Similarly, based on the sustainability index of past research, Jahanbakhsh et al. used machine learning techniques and found that water cycle algorithm is the most precise with a mean absolute error of 2.86 MPa. This research concluded that the amount of cement and super plasticizer is directly proportional to the compressive strength of the concrete and inversely proportional to the sustainability index (Naseri et al. 2020).

Recently, 3d printing of construction materials has gained traction. Scholars have suggested that concrete with adequate sustainability index is expected to be produced by incorporating high amount of industrial waste when 3d printing concrete (Dey et al. 2022). It should be noted that 3d printing of concrete still has a number of technical and processing hurdles to overcome (Schutter et al. 2018). There has been number of research on the non-destructive mechanisms in finding various properties of concrete. Employing similar technique, one researcher observed in a concrete incorporated with industrial waste in the form of coal bottom ash and waste glass sludge as a cementitious additive and replacement of cement has the capability to improve the strength of concrete significantly (Umar et al. 2022).

From the above literature it is observed that, there has been numerous studies on this topic in the context of compressive strength of sustainable concrete at various replacement level of waste materials. The building industry may effectively repurpose leftover brick material by using Crushed Brick Aggregate (CBA) in place of Natural Coarse Aggregate (NCA). As a result, the reliance on NCA

is reduced, and the need for landfill space to store brick debris is removed. It is to be noted that the number of studies that validated their results with numerical modeling by Finite Element Analysis software were limited. In this paper, ABAQUS was used to validate the experimental results by a computer model.

Further, the study of sustainable concrete used in the design of pavements has been scant. In this study various tests such as LA Abrasion test and Impact Value Test were performed to assess the usability of recycled materials in sustainable concrete to be used in pavements. Figure 1a shows brick waste after building demolition and Fig. 1b shows crushed brick aggregate obtained after crushing the brick waste in the lab.

## 2 Methods

### 2.1 Materials

All of the materials used for the study are readily available in the local area. Fine aggregate (river sand), normal coarse aggregate, different sized of crushed clay bricks, ordinary Portland cement, and water were the ingredients used to create the concrete mixes in this study. Below is a detailed discussion of the different materials used in this investigation. Table 1 shows the cement properties obtained from respective tests.

#### 2.1.1 Cement

**Natural coarse aggregate.** The study used coarse aggregate with a size range from 4.75 mm to 20 mm. Natural coarse aggregates from the crusher were used. The sieve analysis of coarse aggregates is carried out as per IS 383:2016.

**Table 1** Cement properties obtained from respective tests

S. No	Properties of Cement	Results
1	Grade and Type	53-grade OPC cement
2	Specific gravity	3.14
3	Fineness (%)	6.56
4	Standard consistency test (%)	29
5	Initial setting time (min)	35
6	Final setting time (min)	510
7	Soundness test (mm)	8

Figure 2a shows the natural coarse aggregate and (b) shows washed river sand used in the experiment.

**Crushed brick aggregate.** Waste bricks were gathered and cement mortar present in them was scrapped off using a trowel. The bricks were then subsequently crushed in the laboratory to produce brick aggregates. The bricks were manually crushed by placing them on a hard surface and string with a hammer until desired size aggregates were obtained. Then, they were sieved into different size fractions, with flaky particles and elongated aggregates being separated and discarded. Both types of coarse aggregates were screened to a maximum size of 20 mm. The sieve analysis of coarse aggregate was carried out according to IS 838-1970.

**Fine aggregate.** Fine aggregate encompasses particles within the size range of 150 microns to 4.75 mm. In order to eliminate detrimental substances and excessively large particles, the river sand underwent a process of washing and screening. The fine aggregate must meet the criteria of being clean, sharp, and composed of natural or crushed sand that complies with the established standards IS 383:2016.

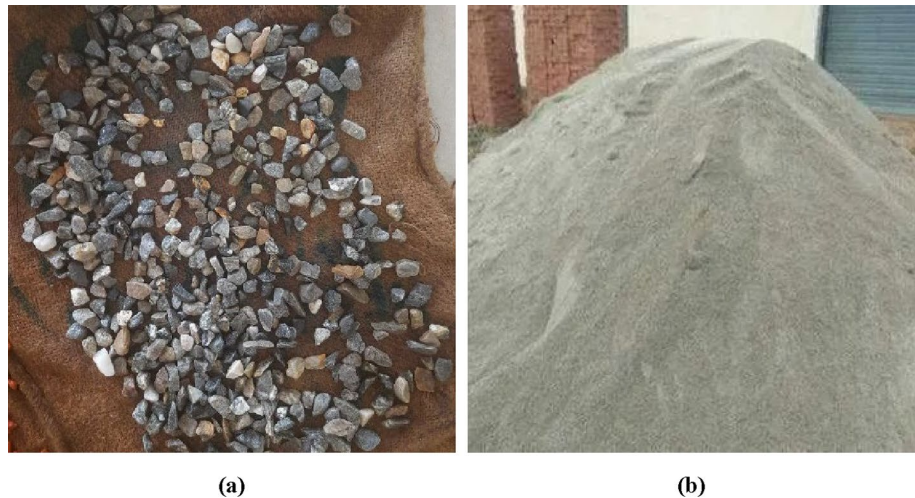
**Fig. 1** (a) Brick waste after building demolition; (b) Crushed brick aggregate



(a)

(b)

**Fig. 2** (a) Natural coarse aggregate; (b) Washed river sand

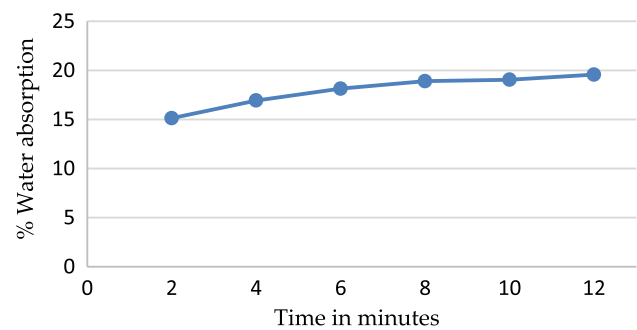


**Water.** For this study, uncontaminated, chemically stable and pH-neutral drinking water at room temperature was used.

## 2.2 Mix Proportion and Methodology

The demolished brick waste was processed in lab and underwent sieving using IS sieves to obtain a suitable aggregate size, which was subsequently used as a replacement.

The mix proportion and designation of M20 concrete recommends combining 1 part cement, 1.5 parts fine aggregate, and 3 parts coarse aggregate. Additionally, a water-cement ratio of approximately 0.45 is employed. However, when incorporating the brick aggregate, which possesses higher water absorption compared to regular coarse aggregate, additional surplus water is added. This was done to overcome the problem of reduced workability as most of the water added to the mix was absorbed by brick aggregate due to its higher water absorption rate. The amount of water added was determined using a novel investigation that yielded a comprehensive depiction of the relationship between water absorption and time for CBA. This facilitates the precise quantification of water absorbed by CBA during the mixing process. The crucial significance of concrete workability is emphasized in this context. A graphical representation was constructed, correlating the percentage of water absorption with time, in order to determine the supplementary water requirement. The water absorption corresponding to time elapsed from initial submergence is given in the figure below. To achieve workable concrete, an additional water content of 18% by weight of CBA is incorporated into each mix for a mixing time interval of 6 min. Figure 3 shows the time vs water absorption graph of Crush Brick Aggregate (CBA).



**Fig. 3** Time vs water absorption graph of CBA

This mix designation indicates that the concrete has a characteristic compressive strength of at least 20 MPa after 28 days of curing.

To investigate the partial replacement of crushed waste brick in fresh concrete, the significance of this waste on concrete strength was observed. In the laboratory, a total of 45 cubes and 10 cylinders were cast using nominal mix M20, with cube sizes of 100 mm × 100 mm × 100 mm and cylinder sizes of 300 mm × 150 mm. The strength of the concrete was evaluated by incorporating crushed brick aggregate with different weight percentages (0%, 10%, 15%, 20%, and 25%) by weight of natural coarse aggregate while maintaining consistent quality and quantity of cement and fine aggregate during the mixing process. The replacement percentage of 0%, 10%, 15%, 20% and 25% are denoted as R0, R10, R15, R20 and R25, respectively. The compressive strength of the cubes was measured at 7, 14, and 28 days, while the tensile strength of the cylinders were determined after 28 days. For the compressive and tensile strength tests, three samples of each day and each replacement mix were cast. Ordinary Portland cement (53 grades) was used in the mix, alongside locally available river coarse sand as the fine aggregate and locally sourced crushed brick aggregate of

Dhulikhel area in Nepal ranging in size from 4.75 mm to 20 mm, as per the experimental study. The concrete mix and curing process was carried out using normal water (Table 2).

### 2.3 Preparation of Specimen

Following the completion of all material property tests, concrete was prepared for mechanical property tests. All materials, including fine aggregate, coarse aggregate, and crushed brick aggregate, underwent sieving using predetermined IS sieve sizes. Their weights were recorded for M20 concrete. The replacement of natural aggregate with crushed brick aggregate was carried out at varying percentages of 0%, 10%, 15%, 20%, and 25% by weight of natural coarse aggregate (NCA). Cement was also weighed, and the water quantity was determined as 0.45 plus an additional 18% by weight of Ceramic Ballast Aggregates (CBA) for each mixture.

Cube and cylinder molds were properly cleaned and oiled prior to pouring the concrete. Crushed brick aggregate, cement, fine aggregate, and natural coarse aggregate were thoroughly mixed using hand-mix method. For five minutes, the measured amount of water was added gradually and blended. The workability of the concrete was then assessed using the Slump Cone test. Upon its completion,

the concrete was poured into the molds and vibrated for 5 s to ensure proper filling and eliminate voids.

The cubes and cylinders were then placed in a laboratory at room temperature and left to cure after a specific duration of 24 h. After this time elapsed, the specimens were de-molded and subjected to curing for specific periods of 7, 14, and 28 days. Upon reaching the designated timeframes, compression and split tensile strength tests were conducted on the cubes and cylinders, respectively.

### 2.4 Modeling and Simulation of Concrete Cube Using ABAQUS

**Simplified concrete damage plasticity.** The Simplified Concrete Damage Plasticity model proves highly suitable for a diverse range of structural simulations involving concrete materials. With its computational efficiency, it offers engineers and researchers a valuable tool in the field of structural analysis and design, providing reasonably accurate predictions of concrete behavior under varying loading conditions.

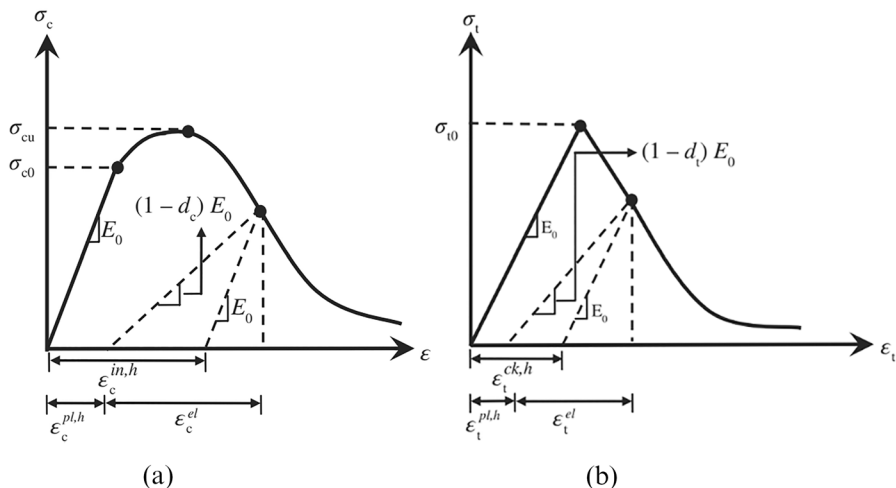
To evaluate the cracking and crushing trends, the model utilizes values for hardening and softening variables. These factors have a role in the loss of elastic stiffness and development of the yield surface. Two independent hardening variables characterize the damage states in compression and tension, denoted as  $\epsilon_c^{pl,h}$  and  $\epsilon_t^{pl,h}$ , respectively. These variables represent equivalent plastic strains in compression and tension, respectively. Figure 4a shows the stress–strain behavior of compressed confined and unconfined concrete Kent and Park model and Fig. 4b shows response of concrete to a uniaxial loading condition compression. Further, Fig. 5 represents response of concrete to a uniaxial loading condition compression.

**Uniaxial compressive behavior.** The uniaxial compressive behavior of concrete pertains to how it reacts when

**Table 2** Sample number for different tests

Ratio	Number of cubes	Number of cylinders
R0	9	3
R10	9	3
R15	9	3
R20	9	3
R25	9	3

**Fig. 4** (a) Stress–strain behavior of compressed confined and unconfined concrete- Kent and Park model; (b) Response of concrete to a uniaxial loading condition compression



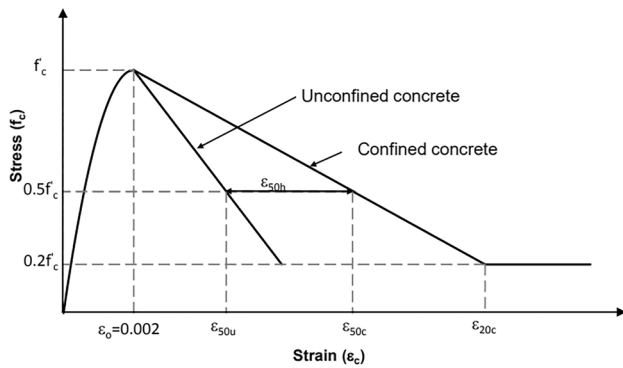


Fig. 5 Response of concrete to a uniaxial loading condition tension

exposed to compressive stress in a single axis or direction. This is a fundamental principle in concrete mechanics and plays a vital role in the design and analysis of different concrete structures. In this study, the Kent and Park parabolic constitutive model was utilized for unconfined concrete, represented by the following equation:

$$\sigma_c = \sigma_{cu} \left[ 2 \left( \frac{\epsilon_c}{\epsilon'_c} \right) - \left( \frac{\epsilon_c}{\epsilon'_c} \right)^2 \right]$$

where  $\sigma_c$  and  $\epsilon_c$  are nominal compressive stress and strain, respectively, and  $\sigma_{cu}$  and  $\epsilon'_c$  respectively represent ultimate compressive strength and the strain of the unconfined concrete specimen.

Park reported that  $\epsilon'_c$  equaled 0.002, and this value was also assumed in this study. The unloading curve slope was regulated by inelastic hardening strain in compression  $\epsilon_{cin,h}$ , which provided the basis for compression damage ( $d_c$ ). Since  $d_c$  rose in proportion to a rise in  $\epsilon_{cin,h}$ , it may be expressed as:

$$d_c = 1 - \frac{\sigma_c}{\sigma_{cu}}$$

A further increase in the hardening cracking strain,  $\epsilon_{ctk,h}$ , the tension damage continued to increase, and this could be expressed as follows:

$$d_t = 1 - \frac{\sigma_t}{\sigma_{t0}}$$

### 3 Results

#### 3.1 Concrete Workability

In order to check the workability of concrete and the consistency of fresh concrete slump cone test was performed based on the IS: 1199-2018. This test plays a vital role in

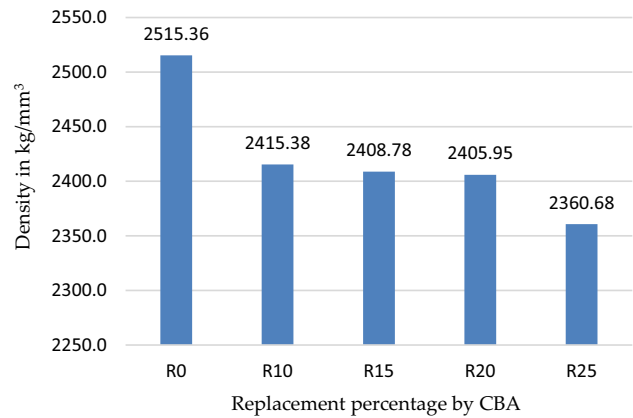


Fig. 6 Density of concrete for different percentage of replacement of NCA

concrete production; it indicates the amount of water added to the concrete. An additional amount of water is added for dry bricks based on the mixing time of the concrete for uniform required workability. Apart from the amount of natural aggregate replaced, the workability was kept approximately constant for each W/C, confirming the efficiency of the adopted mixing procedure in maintaining the workability of concrete.

#### 3.2 Density

The density of fresh concrete was assessed using IS 1199 Part 3-2018. For replacements R0, R10, R15, R20 and R25, the density was observed to decrease by 4%, 4.5%, 5%, and 6% respectively, in comparison to using normal aggregate. This decrease in density was observed while maintaining a consistent W/C ratio of 0.45. The outcomes of the laboratory experiments on the density of fresh concrete, which involved varying percentages of NCA with CBA, indicate that the density of the concrete decreases as the weight percentage of CBA increases. This decrease can be attributed to the lower specific gravity of the brick aggregate. Figure 6 depicts density of concrete for different percentage of replacement of NCA.

#### 3.3 Water Absorption and Specific Gravity

The IS:2386-Part 3-1963 standard was followed to conduct the test. This test aims to determine the specific gravity and water absorption of both coarse aggregates (NCA and CBA) using a perforated basket, and fine aggregate using a Pycnometer.

The findings indicate that the specific gravity and apparent specific gravity of CBA were significantly lower compared to NCA, with reductions of 67% and 10% respectively. However, the water absorption of CBA was significantly

higher than that of NCA, being approximately 72 times greater. These results suggest that CBA possesses characteristics such as lightweight, lower density, and porosity. Figure 7 below displays a graph depicting the specific gravity, apparent specific gravity, and water absorption of both Normal Aggregate and Crushed Brick Aggregate. Additionally, Fig. 8a and b present pictures of the laboratory test of the aggregate using the Perforated basket method and Pycnometer method, respectively.

### 3.4 Sieve Analysis

The process of sieve analysis enables determination of distribution of aggregate particles by size within a given sample, both for coarse and fine aggregates. Its purpose is to ensure compliance with design and production requirements. The method involves passing the aggregates through different standardized sieves as per the IS code

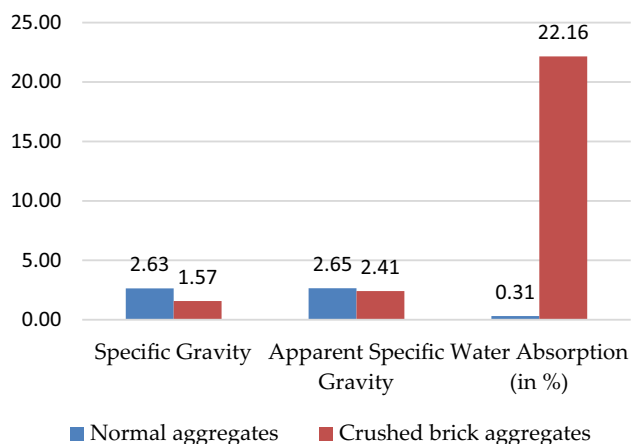
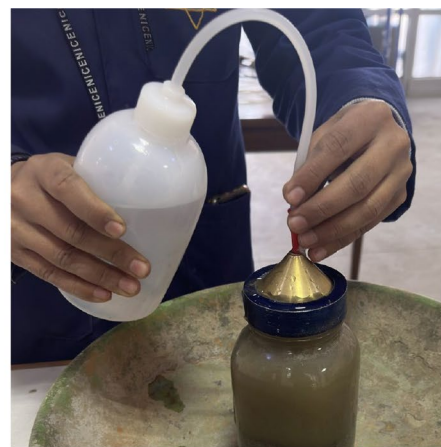


Fig. 7 Physical properties of coarse aggregates

Fig. 8 Water absorption test by (a) perforated basket method; (b) pycnometer method



(a)



(b)

(IS: 2386, Part I-1963) and collecting particles of varying sizes left over on each sieve.

For fine aggregate, the obtained Cu (Coefficient of Uniformity) and Cc (Coefficient of Curvature) values were 3.57 and 1.25, respectively. Similarly, for natural coarse aggregate, the Cu and Cc values were 1.07 and 1.01, respectively, and for brick aggregate, the values were 1.76 and 1.17, respectively. The graphical representation of the sieve analysis of CBA and NCA is shown in below Fig. 9a and b respectively whereas Fig. 10 shows the sieve analysis of fine aggregate.

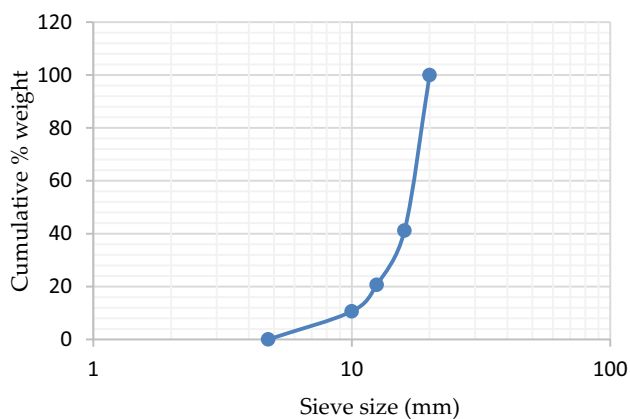
### 3.5 Impact Test of Aggregate

The aggregate impact test was done as per the IS: 2386 (Part IV)-1963 standard. For aggregate impact value, the aggregates need to pass through a 12.5 mm sieve and be retained on a 10 mm IS sieve. There are notable differences in the results between natural coarse aggregate (NCA) and crushed brick aggregate (CBA).

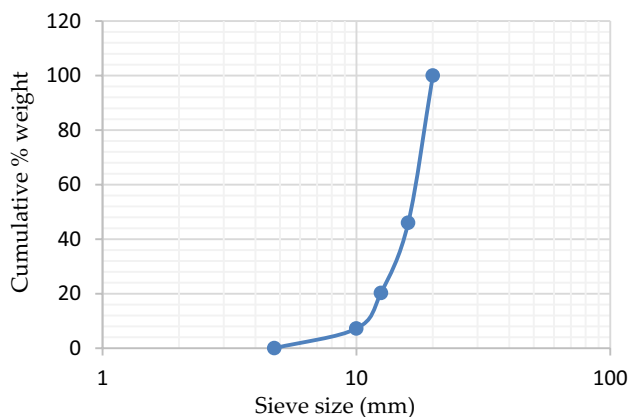
NCA exhibited an impact value of 18.84%, which is less than the specified threshold of 20%. This indicates that the aggregate is exceptionally robust and suitable for use as a road aggregate, particularly for wearing courses, as recommended by the Indian Road Congress.

On the other hand, CBA yielded an aggregate impact value of 45.13%, which exceeds the prescribed limit of 35%. This suggests that this type of aggregate is relatively weaker for road surfacing and is more suitable for use in cement concrete base courses, according to the guidelines set by the Indian Road Congress. Figure 11a shows the graphical representation of Impact value results of NCA and CBA and Fig. 11b shows the LA Abrasion value results of the NCA and CBA.





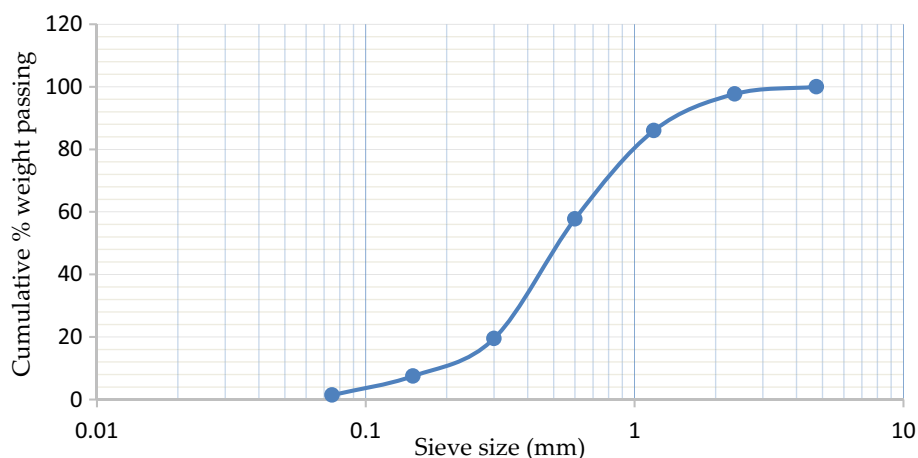
(a)



(b)

Fig. 9 Sieve analysis of (a) crushed brick aggregate; (b) natural coarse aggregate

Fig. 10 Sieve analysis of fine aggregate



### 3.6 Los Angeles Abrasion Test

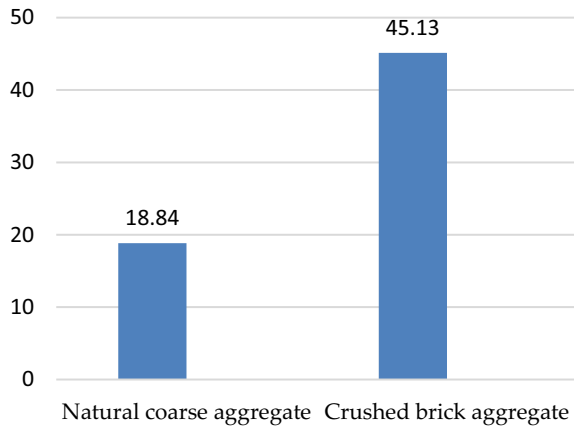
The objective of this test was to determine the abrasion value of coarse aggregates (NCA and CBA) in accordance with IS: 2386 (Part IV)-1963. The test was conducted for grade B. For this purpose, 2500 g of aggregate passing through a 20 mm IS sieve and retained on a 12.5 mm IS sieve, as well as 2500 g of aggregate passing through a 12.5 mm sieve and retained on a 10 mm IS sieve, were used. An 11-charging ball was added to the Los Angeles abrasion-testing machine, and the machine was rotated at a speed of 33 revolutions per minute for a total of 1000 revolutions. Upon completion of the test, the material was discharged and sieved through a 1.70 mm IS sieve.

The Los Angeles abrasion (LA) value of NCA was determined to be 37%, which is less than the threshold of 40%. This suggests that NCA is suitable for use in Bituminous penetration macadam-type pavement.

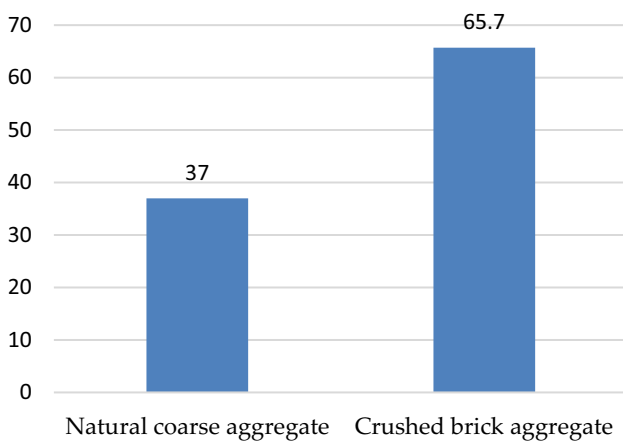
However, the LA abrasion value of CBA was found to be 65.7%, indicating that it alone cannot be used in road pavement applications. Table 3 below shows all the physical properties of the aggregates.

### 3.7 Compressive Strength Test

The compressive strength of the cubical specimen was done as per IS 516: 1959. Figure 12a, b, and c illustrate the average compressive strength of various concrete cube samples at different replacement percentages (0%, 10%, 15%, 20%, and 25%) with crushed brick aggregates, measured at 7, 14, and 28 days, respectively. Figure 13 a and b depict the concrete cube samples in the compressor before and after compression, respectively.



(a)



(b)

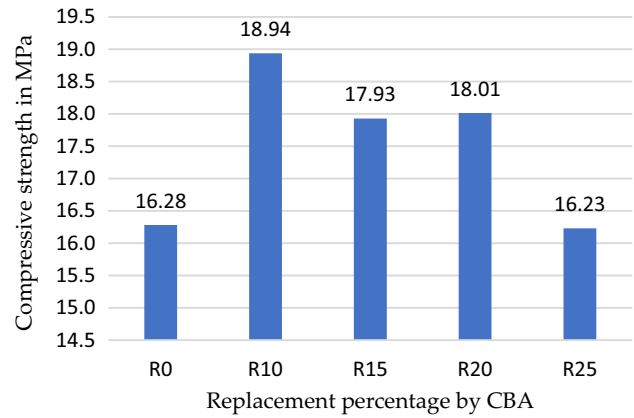
Fig. 11 (a) Impact value of aggregates; (b) LA abrasion value of aggregates

Table 3 Properties of aggregates

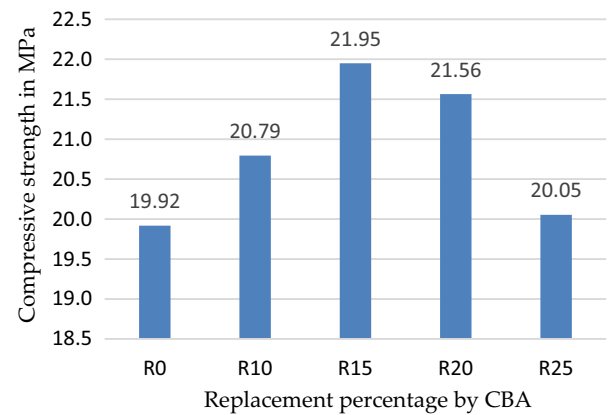
S. No	Properties	Fine aggregates	Coarse aggregates	
			NCA	CBA
1	Fineness modulus	2.31	3.08	3.35
2	Specific gravity	2.64	2.63	1.57
3	Apparent specific gravity	2.71	2.65	2.41
4	Water absorption	0.91%	0.31%	22.16%
5	Impact value		18.84%	45.13%
6	LA abrasion value		37%	65.7%

### 3.8 Split Tensile Strength Test

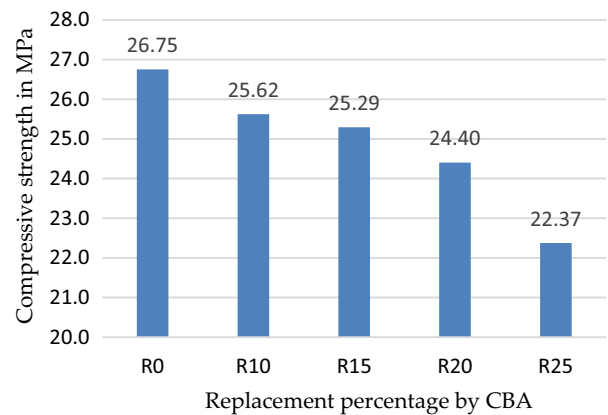
The tensile strength test of the cylindrical specimen was done as per IS 5816: 1999. Tests were done to determine



(a)



(b)

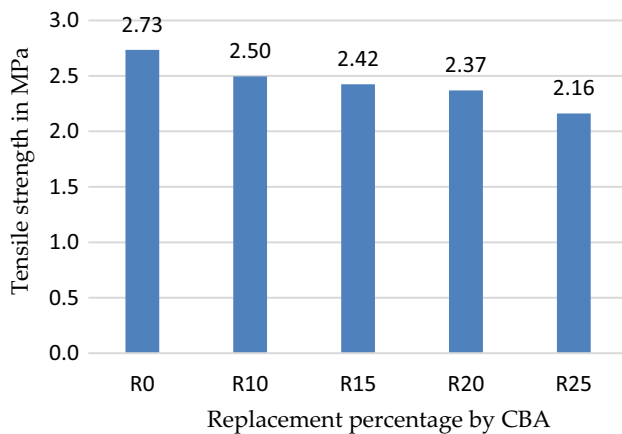
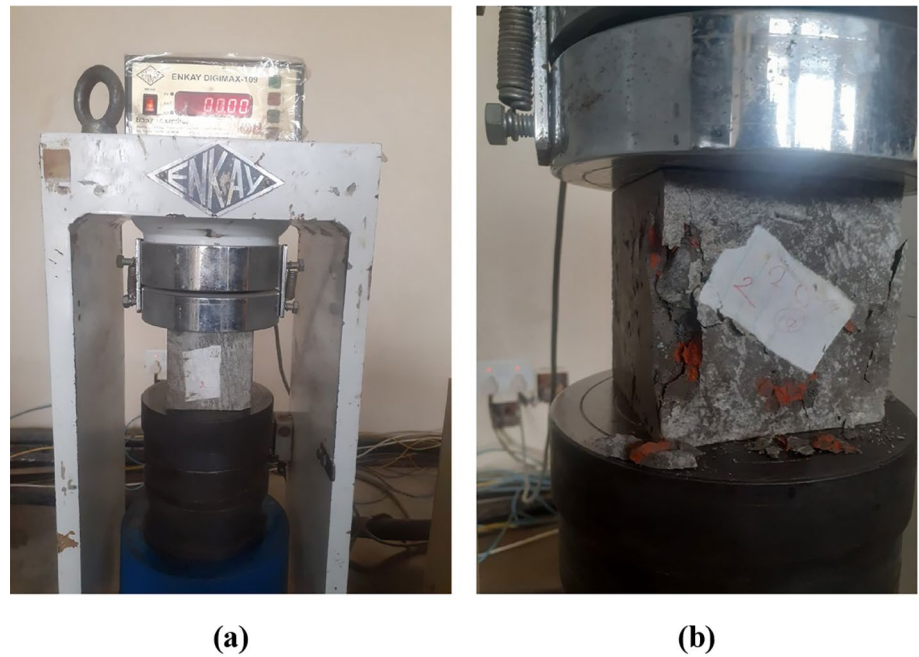


(c)

Fig. 12 Compressive strength of cubes at: (a) 7 days; (b) 14 days; (c) 28 days

the tensile strength after 28 days. The average tensile strength for varying replacement percentages with brick aggregate is presented in Fig. 14. Additionally, Fig. 15a and b display the tensile test picture of the concrete cylinder during and after compression, respectively.

**Fig. 13** (a) Compressive strength test of cube; (b) Cracks formation in cube



**Fig. 14** Tensile strength of cylinder at 28 days

### 3.9 FEM Analysis of the Concrete Behavior Using ABAQUS

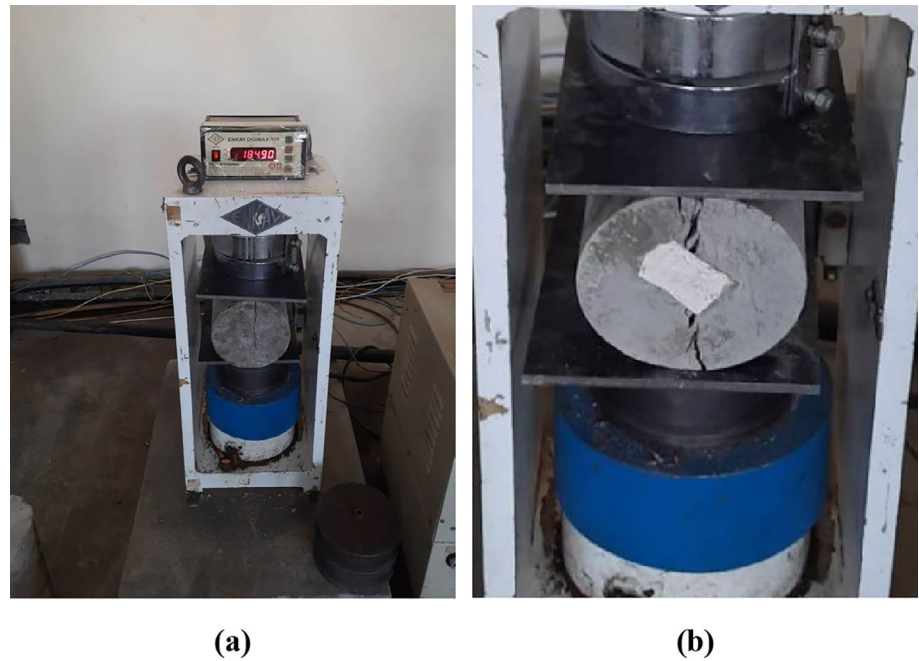
The Abaqus software analysis involved assigning various parameters including density, Young's modulus, yield stress (MPa), inelastic strain, damage parameter, and cracking strain. The Kent and Park parabolic constitutive model was utilized for unconfined concrete in this study. A Poisson's ratio of 0.2 and Young's modulus of elasticity assumed to be root  $f_{ck}$  were applied uniformly across all tests. Additionally, a dilation angle of 40 degrees and a friction coefficient of

0.47 were assumed. The assumptions were made based on the concrete behavior. The material was considered homogeneous, and gradual loadings were applied until concrete failure. Meshing comprised 2197 elements for cubes and 5760 elements for cylinders. Laboratory results of compressive and tensile strength were used to assign parameters, with analysis focusing on cracking patterns, stress, and deformation. The stress–strain curve obtained was compared with typical concrete behavior, although it did not precisely match the stress–strain curve of nominal mix concrete with a grade of M20. This is because there is a reduction in the strength of the concrete in the replacements.

**Compressive strength of concrete cube using ABAQUS.** The simulation and Finite Element Analysis (FEA) conducted in ABAQUS allowed us to obtain the crack pattern and damage of the cube. The cracking pattern and the stresses shown in Figs. 16 and 17 remains almost similar across all samples and the pattern is also similar to the experimental. Nevertheless, the extent of damage increases progressively from R0 through R25. This escalation could potentially stem from a higher substitution of coarse aggregate with brick aggregate. Below, Fig. 16a–e depict the crack patterns and compressive damage at integration points of the cube obtained from Finite Element Analysis (FEA) for concrete mixes: (a) R0; (b) R10; (c) R15; (d) R20; (e) R25 respectively.

Also, Fig. 17a–e depict the Stress components at integration points of the concrete cube obtained from Finite

**Fig. 15** (a) Split cylinder tensile strength test; (b) Cracks formation in cylinder



Element Analysis (FEA) for concrete mixes: (a) R0; (b) R10; (c) R15; (d) R20; (e) R25 respectively.

The concrete cube's response to compressive and stress damages revealed distinct crack patterns and damage parameters. Compressive loads led to localized cracks along stress-concentration points. Compressive stress induced the damage, and interconnected cracking, potentially weakening the structure. This highlights concrete's anisotropic behavior and the importance of considering both stress types in structural design for optimal durability and safety. The result of the FEM is shown in the Table 4 along with the comparison with experimental obtained data.

The results show that the highest compressive stress didn't differ much between the experiment and the FEM simulation. The outcomes were quite similar. The stress-strain diagram of a concrete cube obtained through Finite Element Method (FEM) is illustrated in Fig. 18a, while Fig. 18b represents the relationship between tensile stress and strain for the cube.

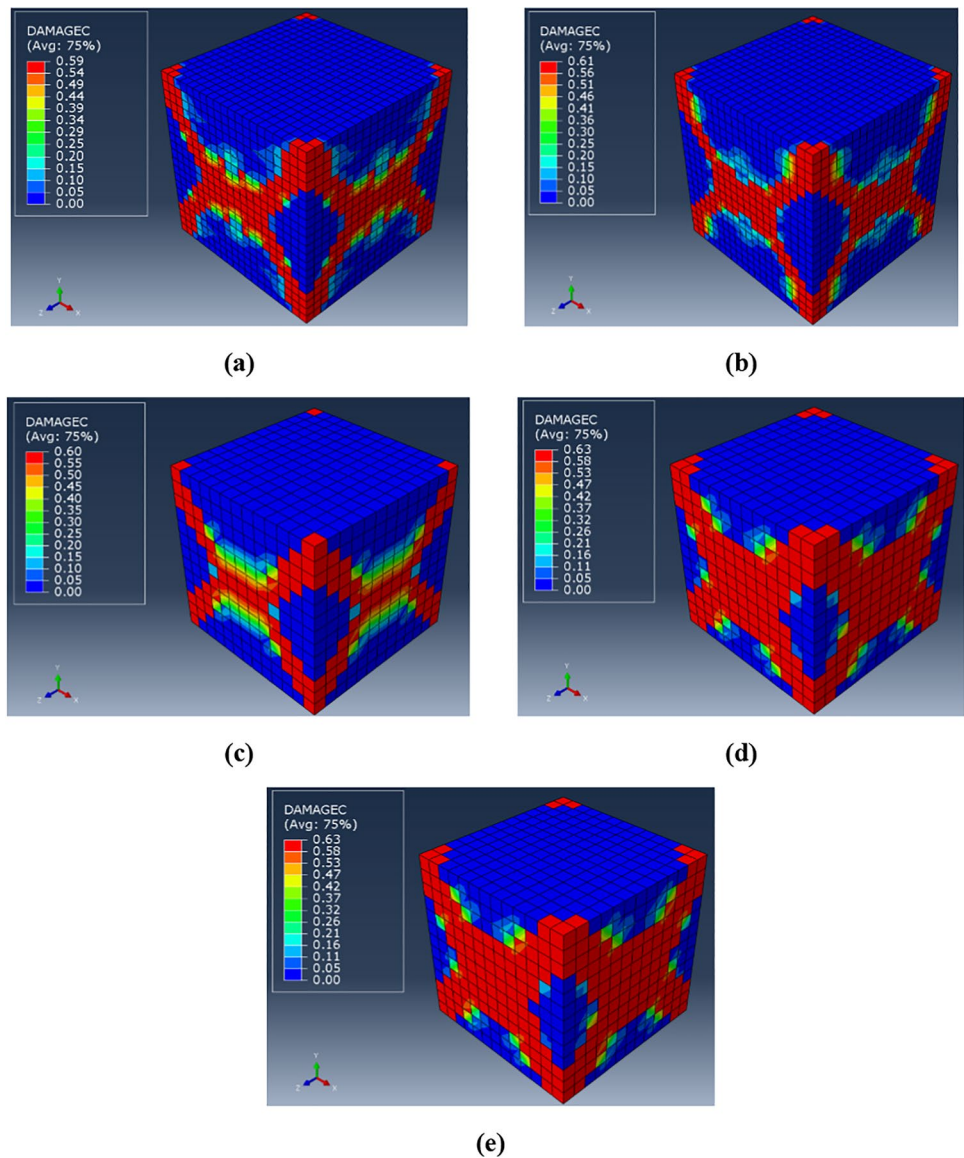
**Split Tensile Strength Test of Cylinder using ABAQUS.** In the Abaqus simulation of the cylinder, a close correspondence is observed between tensile damage values and stress components at integration points. Higher tensile stresses align with increased damage, indicating susceptibility to cracking and failure. The damage values for tension and stress in the concrete cylinders from all the tests were quite alike, as shown in Figs. 19 and 20 below. Stress was predominantly concentrated around the loading support

region, while tension was more pronounced in the central half part of the specimens. Below, Fig. 19a–e show the tensile damage at integration points of the concrete cube obtained through Finite Element Analysis (FEA) for various concrete mixes: (a) R0; (b) R10; (c) R15; (d) R20; (e) R25. Similarly, Fig. 20a–e display the stress components at integration points of the concrete cube obtained from Finite Element Analysis (FEA) for concrete mixes: (a) R0; (b) R10; (c) R15; (d) R20; (e) R25 respectively.

The yield stress vs. inelastic strain graph in Fig. 21a depicts how a concrete material behaves when subjected to increasing strain after reaching its yield point. It illustrates the transition from elastic deformation to plastic deformation, showing the stress at which permanent deformation begins. Similarly, the Yield stress vs. cracking strain graph in Fig. 21b shows the point where cracks begin to develop in a material under stress in tensile behavior. In this context, Fig. 21a illustrates the correlation between the yield stress and the inelastic strain of the concrete, while Fig. 21b depicts the graph showcasing the relationship between the yield stress and the cracking strain of the concrete.

The data indicates minimal variation in Tensile stress results between the experimental and Finite Element Method (FEM) data. As the natural coarse aggregate was replaced more, greater changes in the data were observed. However, the results remain relatively consistent up to R20. The graph between the Tensile stress-strain is shown in Fig. 18b above. Table 5 presents the results of experimentally obtained

**Fig. 16** Crack pattern and compressive damage at integration points of the cube obtained from FEA for different concrete mixes: (a) R0; (b) R10; (c) R15; (d) R20; (e) R25

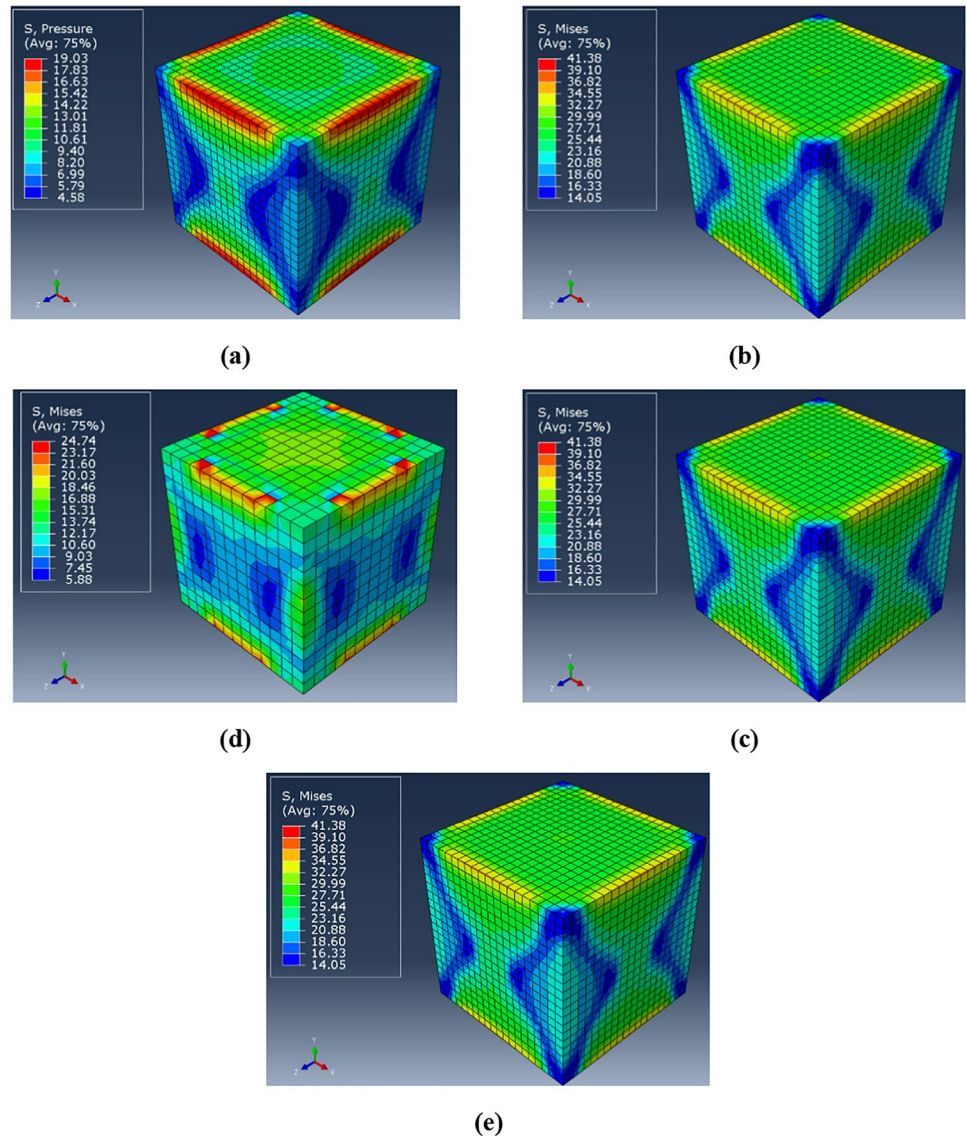


compressive stress and those derived from Finite Element Method (FEM).

The comparison between experimental and lab-obtained stress data revealed noticeable variations. Compressive stress values demonstrated a consistent decrease across the R0, R10, R15, R20, and R25 mixes, with reductions of 5.68%, 4.94%, 4.78%, 4.20%, and 3.54%, respectively. Conversely, tensile stress values obtained from Finite Element FEM analysis showed a gradual increase, with deviations of 1.80%, 3.10%, 3.97%, 3.27%, and 6.49% higher than experimental values for the same mixes. These results underscore significant fluctuations in both compressive and tensile stress

across concrete mixes incorporating crushed brick aggregate (CBA) as a substitute for natural coarse aggregate (NCA). The consistent decrease in compressive stress suggests a potential weakening effect due to differences in mechanical properties and bonding characteristics between CBA and NCA. In contrast, the gradual increase in tensile stress values derived from FEM analysis implies the material's results of the strength varies with the replacements in the concrete. FEM's assumption of linear material properties and idealized geometries may not fully capture the nonlinear behavior of concrete, particularly with increasing proportions of crushed brick aggregate. Additionally, limitations in accounting for

**Fig. 17** Stress components at integration points of the concrete cube obtained from FEA for different concrete mixes: (a) R0; (b) R10; (c) R10; (d) R20; (e) R25

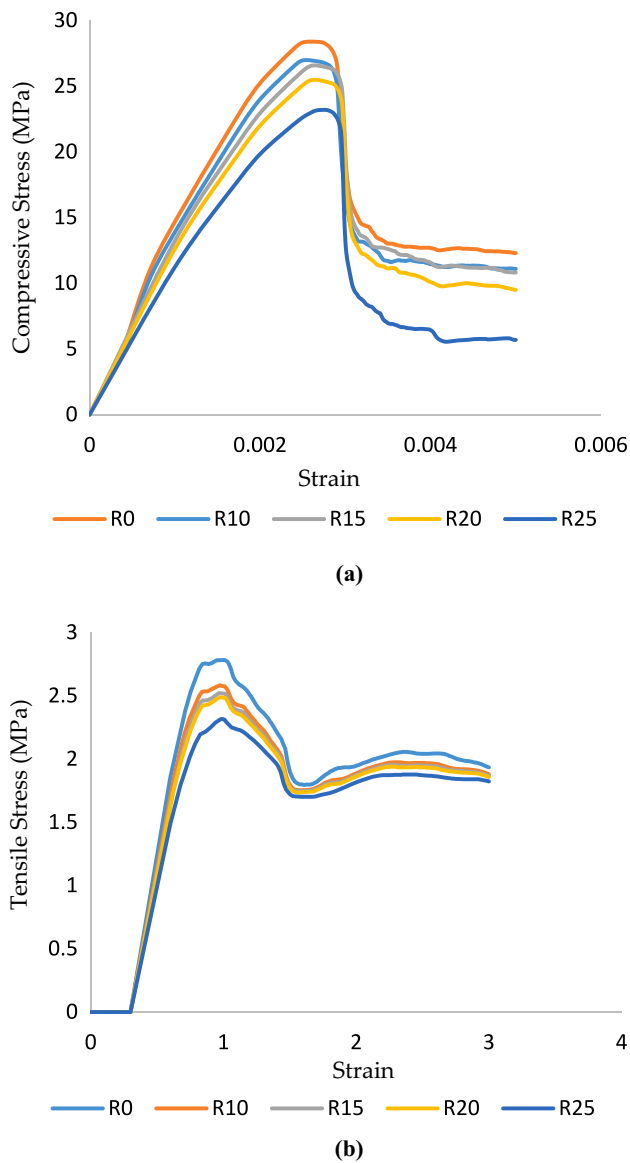


**Table 4** Result of compressive stress obtained experimentally and from FEM

Concrete mix	ABAQUS mesh type-size	Total nodes	Total elements	Maximum stress of Failure (MPa)		Variations from experiment (%)
				FEM	Experimental	
R0	C3D8R	2744	2197	28.36	26.75	5.68
R10	C3D8R	2744	2197	26.95	25.62	4.94
R15	C3D8R	2744	2197	26.56	25.29	4.78
R20	C3D8R	2744	2197	25.47	24.4	4.20
R25	C3D8R	2744	2197	23.19	22.37	3.54

the heterogeneity and variability of real-world concrete mixtures may contribute to discrepancies between predicted and observed stress levels. Further refinement of modeling

approaches is necessary to accurately predict stress behavior in concrete mixes containing CBA.



**Fig. 18** (a) Compressive stress vs strain plot; (b) Tensile strength vs strain plot

## 4 Discussion

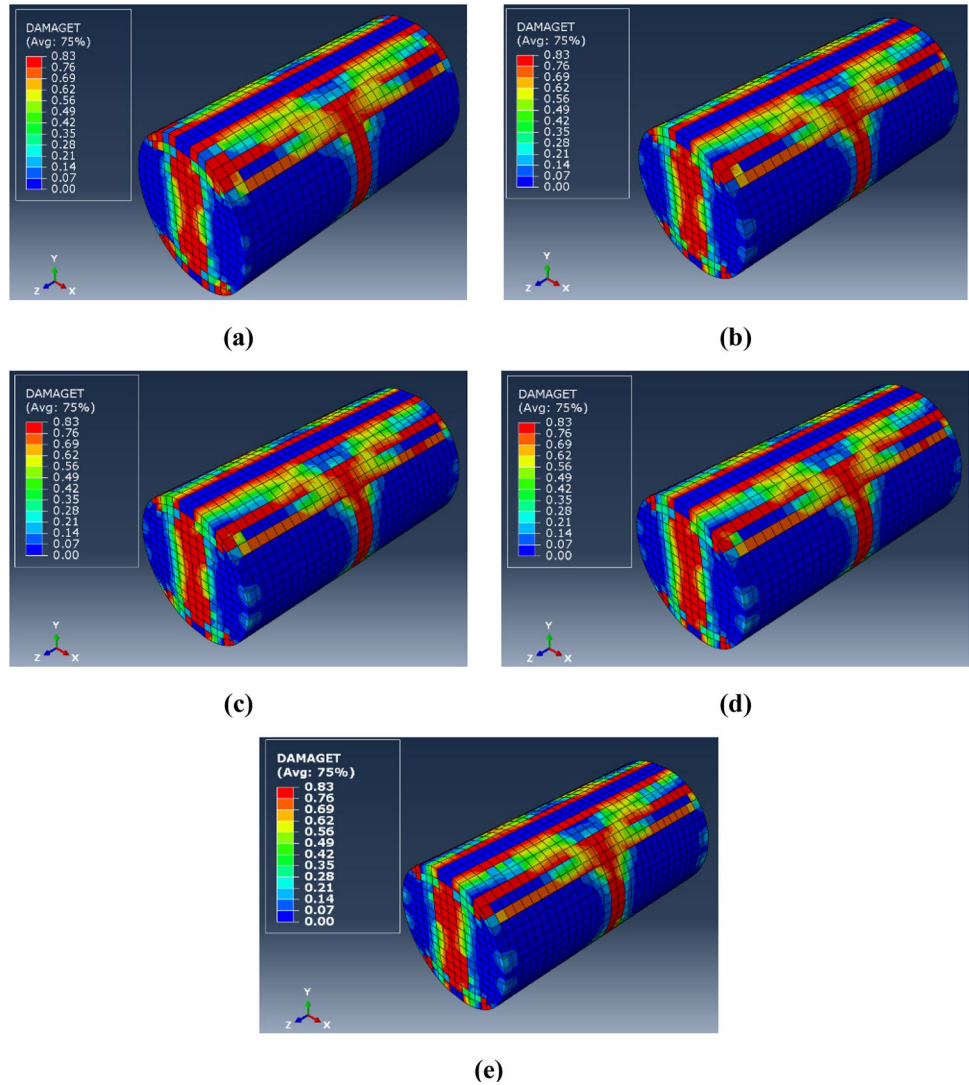
The results from the compressive strength test reveal a reduction in compressive strength compared to a normal M20 concrete cube sample as the replacement percentage increases. There is a 4.22% reduction in compressive strength when compared to the regular M20 concrete cube sample for R10. This reduction suggests that the

addition of replacement material at a rate of 10% moderately reduces the overall strength of the concrete. There is a noticeable decrease in compressive strength as the replacement percentage rises. When compared to standard M20 concrete, R15 shows a reduction of roughly 5.46%. For R20, the reduction in strength rises to about 8.78%. With a significant decrease of about 16.37%, R25 shows the largest decline. Most of the research hasn't defined the amount of water cement ratio used during the partial replacement so the compressive strength is varying with same replacement percentage as compared to this research. Similarly, the results from the split cylinder tensile strength test reveal a reduction in tensile strength compared to a normal M20 concrete cylinder sample as the replacement percentage increases. On comparing R10's concrete cylinder sample with a typical M20 cylinder, the tensile strength is 8.4% lower than that of regular M20 concrete. The tensile strength decreases more noticeably as the replacement percentage rises. The reduction for R15 is 11.35% and that for R20 is 13.19%. R25 has had the greatest reduction, with a significant drop of about 20.88%.

The study also observed a relationship between the concrete's strength and density. The density of concrete has a positive correlation with both its tensile and compressive strengths. When low-density CBA replaces high-density NCA in the concrete, the density lowers and the concrete's compressive strength gradually declines. The decrease in load-bearing capability and looser material packing are the reasons for this drop. In a similar manner, when density drops, concrete's tensile strength also declines. This decrease in tensile strength in low-density concrete is due to poorer particle interlocking and less bonding. The R20 mix likely has a more favourable Interfacial Transition Zone (ITZ) configuration due to its lower proportion of crushed brick CBA than R25, resulting in better bonding between the cement paste and aggregate particles and increased compressive strength. Conversely, the higher proportion of CBA in the R25 mix may lead to a less optimal ITZ configuration, resulting in poorer bonding and decreased compressive strength. An optimal ratio of CBA, approximately 20% or less, appears to be ideal for maintaining strong bonds between the bricks, aggregate, and cement within the concrete mixture.

The ABAQUS software was used to analyze the graphs that displayed tensile stress vs. strain, compressive stress vs. strain. The precision and dependability of the simulation model are confirmed by the comparison of result between

**Fig. 19** Tensile damage at integration points of the concrete cube obtained from FEA for different concrete mixes: (a) R0; (b) R10; (c) R15; (d) R20; (e) R25

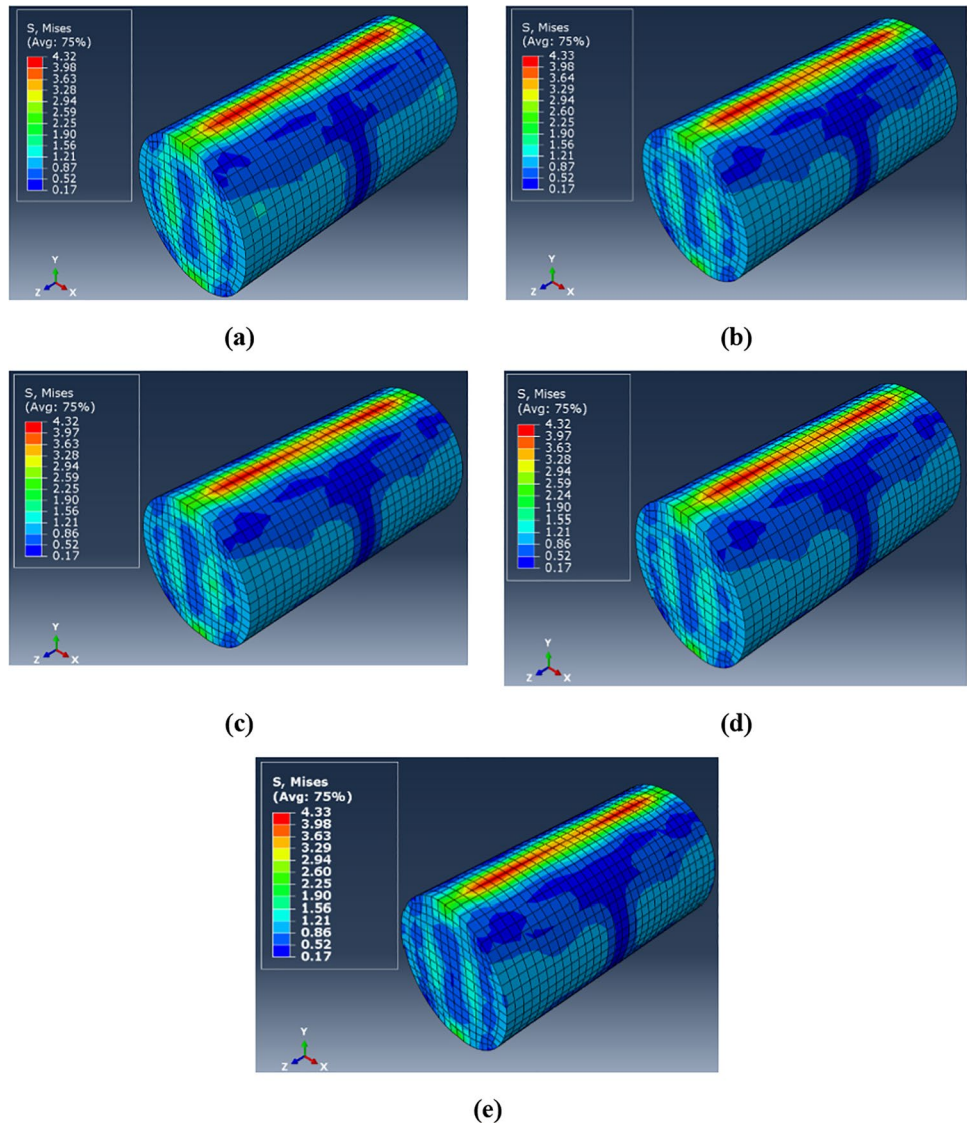


experimental findings and stress–strain curves produced by FEM. The observed tendencies toward decreasing stress parameters as strain increases are consistent with both empirical observations and theoretical predictions. After assigning parameters like density, yield stress, inelastic strain, damage parameter, and cracking strain, meshing was conducted, and simulations were performed. The outcomes included observing cracking patterns in compressed cubes, the distribution of stress on the concrete cube, and the tensile strength of the cylinder. Cracking patterns on the cubes appeared diagonally with vertical stress applied directly. Similarly, in the cylinder's tensile test, stress was

downward, and observed cracking matched laboratory tests. This alignment confirms the accuracy of assigned parameters and loading conditions. Final results provided stress–strain parameters for both compressive and tensile behaviors of the concrete cubes. However, slight discrepancies were noted compared to laboratory tests, attributed to assumptions in parameter selection and specimen meshing. Additionally, the lack of precise values for Poisson's ratio and Young's modulus for various concrete components led to stress pattern variations. A limitation of the FEM study was the need to assign properties to individual concrete components before analysis.

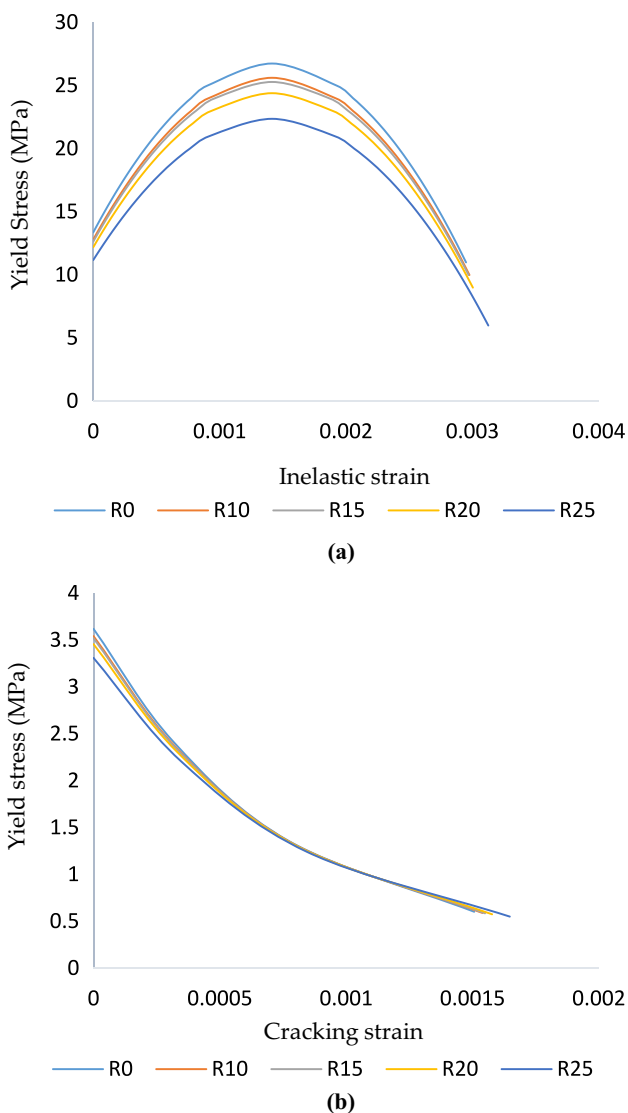


**Fig. 20** Stress Components at integration points of the concrete Cube obtained from FEA for different concrete mixes: (a) R0; (b) R10; (c) R15; (d) R20; (e) R25



Further study can be done in order to determine the variation in strength of concrete with the replaced aggregate amount with greater sensitivity. Investigations and statistical analysis can be done to accurately predict the strength of concrete based on the amount of brick aggregate replacing normal aggregates. Long-term durability studies are essential to assess the performance of low-density concrete under various environmental conditions and loading scenarios, providing insights for sustainable construction practices. The chemical composition of the brick and brick classes may have

a certain effect on the concrete strength when used as CBA, which can be verified in detail. Strength of CBA may depend on the ages it has been in use and this can also be included in future research. The FEM concrete parameters can be assigned individually with their properties and the actual simulations can be done and the results need to be observed. Further exploration on the environmental perspective of the the concrete and bricks thrown into the surrounding can be done and the material costing can also be identifies for the real life scenarios.so that CBA can be very useful in future.



**Fig. 21** (a) Yield stress vs inelastic strain plot in compressive behavior from experiment; (b) Yield stress vs cracking strain plot in tensile behavior from experiment

### 5 Conclusions

The analysis investigates how different levels of replacing crushed brick aggregate (CBA) affect concrete strength and density. Results show a consistent decrease in both compressive and tensile strength with higher replacement percentages, attributed to increased porosity and poor bonding. Lower-density concrete also exhibits reduced strength. Finite Element Method (FEM) results support these findings. Optimal replacement is determined to be 20%, maintaining at least 91.22% of the strength of typical concrete. This suggests potential applications in various concrete uses like landscaping features, non-structural components, light-duty structures, temporary constructions.

By substituting CBA for NCA, there’s potential to optimize material usage in construction, potentially reducing overall material requirements. Additionally, incorporating CBA into concrete mixes can contribute to resource conservation by utilizing recycled or byproduct materials, thus reducing the demand for virgin resources. Moreover, the use of CBA aligns with sustainability goals within the construction industry, promoting more environmentally friendly practices. However, challenges such as ensuring consistent quality and availability of CBA, managing costs, and maintaining performance and durability standards must be addressed. Overcoming these obstacles requires collaboration and innovation across stakeholders in the construction sector to fully realize the benefits of utilizing crushed brick aggregate in concrete construction.

Replacing NCA with CBA shows significant strength in tests. Yet, the chemical composition and classification of the brick (first, second, or third) could affect concrete strength when using CBA, requiring detailed examination in separate tests. Additionally, the strength of CBA might vary based on the brick’s age and the environmental conditions it has experienced. Bricks from different regions with various climates may display distinct strengths, indicating potential research directions.

**Table 5** Result of compressive stress obtained experimentally and from FEM

Concrete mix	ABAQUS mesh type-size	Total nodes	Total elements	Maximum stress of Failure (MPa)		Variations from experiment (%)
				FEM	Experimental	
R0	C3D8R	6727	5760	2.78	2.73	1.80
R10	C3D8R	6727	5760	2.58	2.5	3.10
R15	C3D8R	6727	5760	2.52	2.42	3.97
R20	C3D8R	6727	5760	2.45	2.37	3.27
R25	C3D8R	6727	5760	2.31	2.16	6.49

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## Declarations

**Ethics Approval** Not applicable.

**Consent to Participate** All authors were highly cooperative and involved in research activities and preparation of this article.

**Consent for Publication** All authors agreed to publish this research article.

**Availability of Data** The data supporting the findings of this study are available within the article.

**Competing Interests** The authors have no relevant financial or non-financial interests to disclose.

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