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Research Article

Mechanical performance of 100% recycled aggregate concrete (RAC) bricks

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Abstract: Urbanization and modern development of expanding infrastructure have resulted in large construction activities. With the expeditious growth in the construction industry, the rate of demolition has also increased. This is causing considerable increase in Construction and Demolition (C&D) waste all around the globe. To minimize its impact on society and environment, preventive measures are required to be taken on urgent basis, and for this reason construction industry has proposed the use of recycle concrete aggregates in different applications and there is dire need to investigate experimentally the properties of concrete products made using Recycled Aggregate Concrete (RAC). In this regard, this study focused to investigate the mechanical properties of 100% RAC bricks prepared with two different compositions with respect to coarse to fine aggregates ratio (i.e., 70:30 and 60:40), cement dosage (i.e., 10% and 15% by weight of total aggregates) and casting pressure (i.e., 25 MPa and 35 MPa). Recycled concrete aggregates required for this study were produced by crushing tested concrete samples having compressive strength of 21 MPa to 28 MPa. Mechanical tests were performed on bricks to determine their compressive strength, flexural strength, shear strength, impact energy in compression and flexure. In addition to these destructive tests, non-destructive (rebound hammer and ultra-sonic pulse velocity) tests were also performed. To draft a comparison, Natural Aggregate Concrete (NAC) bricks and first class burnt clay bricks were also tested. The results indicated that the compressive strength of NAC bricks was about 30% higher than the compressive strength of RAC bricks. However, RAC bricks exhibited higher compressive strength as compared to burnt-clay bricks. The flexural strength of RAC bricks containing 60% coarse aggregates and 40% fine aggregates and RAC bricks containing 70% coarse aggregates and 30% fine aggregates was found to be almost similar but their flexure strength was 37.3% and 20.7% lesser than their corresponding NAC bricks. Flexure strength of RAC bricks and burnt clay bricks was found to be almost same. Qualitative assessment by ultrasonic pulse velocity (UPV) tests showed that the NAC and RAC bricks were of good quality as per the standard criteria. The findings of this study indicated that RAC bricks satisfied the strength requirements as stated by local and international standards. Further, RAC bricks performed better than commonly used first class burnt clay bricks. Production and use of RAC bricks in masonry structures will not only help to conserve the depleting resources of natural aggregates and clay but also help to protect our environment from pollution by reducing CO_2 emission caused by the coal-burning as fuel in kilns for the manufacturing of burnt-clay bricks.

Keywords: Bricks, concrete, recycled aggregates, mechanical performance, eco-friendly.

1. Introduction

In construction sector of Pakistan, burnt clay bricks are extensively used as construction units. Pakistan is the third largest producer of burnt clay bricks in South Asia after India and Bangladesh. Around 18000 brick kilns are operating all around the Pakistan and are producing more than 45 billion of bricks every year (Iftikhar et al., 2020; Mukhtar et al., 2022; 'Pakistan–Business Recorder', 2017). Coal is one of the major fuels used for the production of brick in kilns as the coal reserved estimated to be around 185.175 billion tons, ranking Pakistan to be the fourth richest country in the world with respect to coal reserves (Rehman et al., 2017). From 1991 to 2017, average coal consumption by the brick manufacturing industry was estimated to be around 3025.5 metric tons according to Census and Economic Information Centre (Pakistan-CEIC, 2017). In addition to coal, other fuels used for the production of bricks are biomass such as crop residue, wood, and fly ash, plastics, waste tyres and other materials (Co et al., 2009; Hossain et al., 2019; Rajarathnam et al., 2014). In Pakistan, around 99% of the kilns producing bricks are Fixed Chimney Bull's Trench Kiln (FCBTK) and the remaining 1% are Induced Draught Zigzag Kiln (IDZZK). The annual estimation of CO_2 emission by one unit of FCBTK and IDZZK in Pakistan are over 14000 and 5700 tons, respectively (Rauf et al., 2022).

In Pakistan, particularly in metropolitan cities, smog is becoming a severe issue in winter season which is a combination of smoke and fog. It has almost become fifth season in Pakistan, especially in Lahore and its surroundings according to the Pakistan Institute of Development Economics (PIDE) (Naz and Abedullah, 2022; Yousaf et al., 2021). Major causes of smog include irregular burning of fuel without pollution control measures, burning of various fuels (such as tyres, coal, crop residue etc.) in brick kilns, uncontrolled construction activities resulting in dust (Naz and Abedullah, 2022; Yousaf et al., 2021). Brick kilns are also emitting other air pollutants to the environment such as SO_2, CO_2, CO, NOx, Pb etc. without any controlled treatment to prevent the environment from these pollutants (Asif et al., 2021; Bhat et al., 2014; Rajarathnam et al., 2014; Shaikh et al., 2020). As a result of smog in winter particularly from December to January, Lahore has been ranked the second most polluted city in the world in 2020 (Sarfraz, 2020). To mitigate the impact of brick kilns on the production of smog in winter season, local government (LG) department is trying its best to convert the brick kilns to Zig Zag technology and around 40% of the total kilns have been converted to this technology (CCAC, 2022).

With the increase in the population at a growth rate of 2.4% as per 2017 census results (Basit et al, 2018) and extensive urbanization in the recent years (Blank et al, 2014) in Pakistan, the demand of the construction materials for building construction units is increasing day by day. In the developing countries, like Pakistan, burnt clay bricks are the main construction material to build residential units. Therefore, production of large number of such bricks not only causes environmental pollution but also put huge burden on the natural resources of raw material (i.e., natural clay) required for making bricks. Globally, the demand for raw materials used in construction has increased and will be doubled by 2030 (Strategy & System (ESPAS), 2015). Worldwide, construction industry consumes 36% of the total energy and is one of the main sources of greenhouse gas (GHG) emissions (Ncube et al., 2021). With the depletion of the natural resources as well as adverse effect of process of brick manufacturing on the environment, countries such as China and India are minimizing the use of clay in bricks up to a great extent and shifting towards the use of sustainable materials for the manufacturing of bricks (Mukhtar et al., 2022; PN et al, 2018; Zhang, 2013).

Along with bricks, concrete is one of the major construction materials used worldwide. Concrete constituents are aggregates (around 60-70 %) and cementitious materials. With the expeditious growth in the construction industry, the rate of demolition has also increased due to the complex interaction of concrete material with environment which results in the deterioration of structural concrete. This has caused considerable increase in massive quantities of Construction and Demolition (C&D) waste all around the globe which leads to the serious environmental problems, including disposal problem (Coelho & de Brito, 2012; Marzouk and Azab, 2014; Yu et al., 2018). Ecologists have expressed serious concerns over the alarming growth of C&D waste which is 30% of the solid waste (Rodríguez et al, 2015). The total amount of solid waste generation in Pakistan is around 54000 to 87000 metric tons per day (Nadeem et al., 2022), which includes around 30% of the C&D waste (Iqbal & Baig, 2016). To reduce the impact of the C&D waste on the environment, the concept of sustainable construction has been introduced in the recent years.

Recycling of waste concrete is conceived as an eco-friendly approach and provides sustainable development in construction industry. Recycled Concrete Aggregates (RCAs) are one of the major reusable materials obtained by crushing and sorting of the C&D waste that has reduced the growing demand of natural aggregates to some extent. In this way, the life cycle of the construction materials is also enhanced.

To overcome smog problem and to minimize the burden on natural resources, there is a dire need to explore different construction materials. RCAs have been extensively used in concrete commonly known as Recycled Aggregate Concrete (RAC) which can be used in various applications (Amin et al, 2021; Kurda et al, 2019; Makul et al., 2021; Nedeljković et al, 2021; Pacheco et al, 2019; Sasanipour and Aslani, 2020; Silva et al, 2021; Hameed et al., 2022). Chu et al. (2021) studied the impact of packing of natural (NA) and recycled aggregates (RA) on the properties of concrete block. To avoid the inferior performance by the use of RA in the concrete, aggregate packing concept was used. After pouring the fresh mix in the mold, compressive load of 500 kN at a loading rate of 10 kN/s was applied on all the specimens. Particle packing phenomenon found to be the major factor in the improvement of the properties of RA concrete blocks. With the application of packing, 94% improvement in the strength of RA concrete was observed as compared to the NA concrete. Moreover, with the optimization of packing, 156% increase in the compressive strength of RA concrete was analyzed. Pederneiras et al. (2020) analyzed the impact of incorporating recycled aggregates obtained from C&D waste on the mechanical and water absorption properties of concrete paver blocks. Both Recycled Fine Aggregates (RFA) and Recycled Coarse Aggregates (RCA) were incorporated by 100% and the results were compared with the blocks containing 0% C&D waste. Three conditions of aggregates i.e., dry, washed and saturated were studied. The resulting blocks were reported to have satisfactory properties for use as paving blocks in streets with low movement and traffic load.

Literature review indicated that very limited research is available on the use of RCAs in the manufacturing of RAC bricks. Since manufacturing of clay bricks used in the construction as basic masonry unit consumes vast resources of natural clay which results in scarcity of agriculture land, there is need to explore other cost-effective materials to manufacture masonry units. In this regard, use of RAC bricks in the construction of residential units will not only help to conserve natural resources of clay but also help in effective management of C&D waste which otherwise causes environmental pollution. Keeping this fact in mind, research studies are required to be done to formulate and suggest best mix design of RAC to be used in the manufacturing of concrete masonry units. For this purpose, under the scope of this study RAC masonry units were manufactured and their mechanical properties were evaluated and compared with natural aggregates concrete (NAC) bricks as well as clay bricks. Novelty of this work lies in manufacturing of RAC bricks by Compression Casting Technique (CCT) and their characterization.

2. Materials and methods

2.1. *Materials*

Ordinary Portland cement confirming to requirement of ASTM C150 (ASTM C150, 2016) was used as a binding material in this study. Both recycled fine and coarse aggregates were obtained by crushing of commercially tested concrete cylindrical and cubic specimens having compressive strength range of 21 MPa to 28 MPa. Following step by step procedure was adopted to produce RCA:

- Tested concrete specimens were broken down into pieces with the help of a hammer.
- The broken pieces were then passed through jaw crusher to get particle size range of 30 mm to 70 mm.
- Material obtained after jaw crushing was then passed from roller crusher to get aggregates having maximum particle size of 10 mm.
- Aggregates obtained after roller crushing were separated into coarse and fine aggregates using ASTM Sieve 4.

Production process of RCA is shown in Figure 1. Physical and mechanical properties of RCA are presented in Table 1. For the comparison purpose, concrete bricks were also prepared using natural aggregates. Locally available crushed stone and river sand were used as coarse and fine aggregates, respectively to prepare concrete mix of natural aggregates. Physical and mechanical properties of natural aggregates are also presented in Table 1. Locally available admixture based on carboxylic acid derivatives was used as superplasticizer.

Figure 1. Production process of RCA.

Table 1. Physical and mechanical properties of recycled and natural aggregates.

Property	Testing Standards	Recycled aggregates		Natural aggregates	
		Coarse	Fine	Coarse	Fine
Specific Gravity	ASTM C 127 & ASTM C128	2.457	1.953	2.776	2.612
Water Absorption (%)		3.32	12.94	2.09	0.53
Moisture Content (%)	ASTM C566	3.84	6.73	0.13	0.60
Flakiness Index (%)	BS 812 105.1	21.66	-	36.32	-
Elongation Index (%)	BS 812 105.2	13.63	-	23.12	-
Rodded Bulk Density (kg/m³)	ASTM C29	1454.45	1367.34	1524.86	1774.68
Loose Bulk Density (kg/m³)		1297.98	1284.7	1409.48	1622.49
Fineness Modulus	ASTM C136	-	1.6	-	2.42
Los Angeles Abrasion Value, %	ASTM C131	23.54	-	11.55	-
Aggregate Crushing Value, (%)	BS 812-110	20	-	17	-
10% Fine Value, TFV (kN)	BS 812-111	135	-	157	-
Aggregate Impact Value, (%)	BS 812-112	17	-	13	-

2.2. Mix proportions

Four design mixes as given in Table 2 were used to make RAC and NAC bricks for this study. In the nomenclature "70C" stands for 70% content of coarse aggregates and "30F" for 30% content of fine aggregates. Similarly, for other designations "60C" stands for 60% content of coarse aggregates and "40F" for 40% content of fine aggregates. It is pertinent to mention here that for initial trials in this study, eight RAC mixes with respect to ratio of coarse to fine aggregates (i.e., 40C60F, 50C50F, 60C40F & 70C30F) and cement contents of 10% and 15% (by weight of total aggregates) were used to make bricks at casting pressure of 25 and 35 MPa. It was observed for RAC mixes made using 15% cement and w/c of 0.5 that some quantity of added water was expelled from brick moulds when desired casting pressures were applied. Based on this observation, w/c ratio was adjusted accordingly and kept as 0.35 for RAC mixes containing 15% cement by weight of total aggregates. Compressive strength values of these bricks are presented in Figure 2, where it is observed that mixes having coarse aggregates content greater than 50% of the total aggregates exhibited higher values of compressive strength. Based on the compressive strength results of initial trials, for further investigation of mechanical performance, two RAC mixes out of above mentioned eight mixes were selected as presented in Table 2 along with NAC mixes. To prepare concrete, coarse aggregates in saturated surface dry (SSD) conditions were used. Initially, fine and coarse aggregates were mixed in the mixer for 2 minutes. After that, cement content by weight of total aggregates [refer to Table 2] was added to the mixer and dry ingredients were mixed for 1 minute to homogenize the mix. After dry mixing, water and superplasticizer were added gradually.

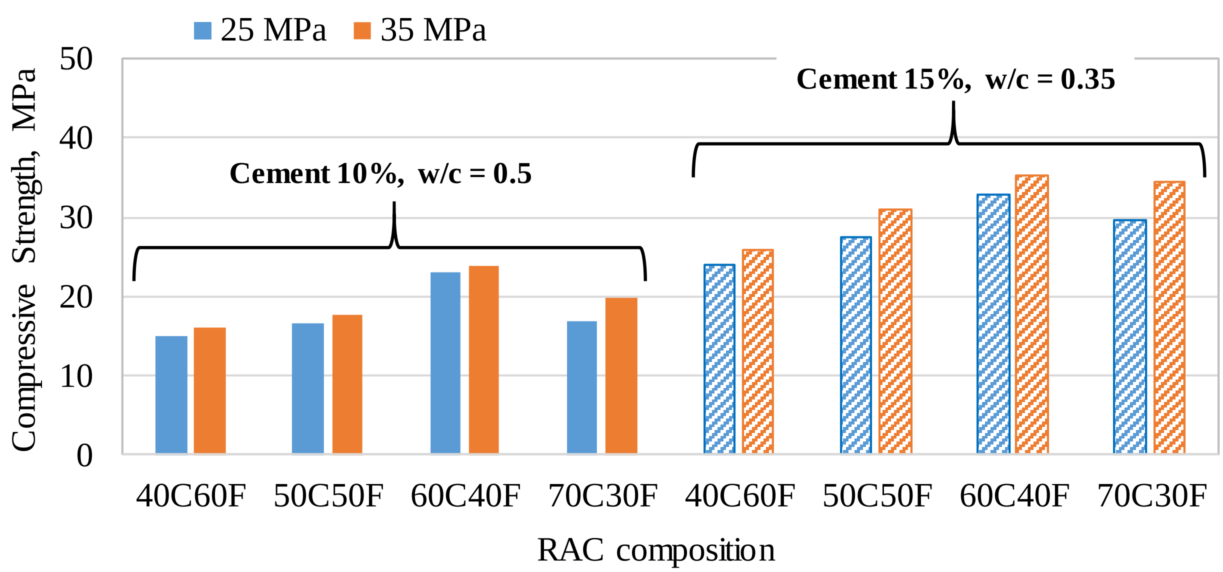


Figure 2. Compressive strength: effect of casting pressure, ratio of fine to coarse aggregates and cement content.

2.3. Preparation of bricks

To prepare the brick specimens of size 226 mm x 113 mm x 75 mm, specially designed molds to withstand the required applied pressure were used in this research. After preparing, concrete was poured into brick mold in three layers and each layer was tampered with 25 blows of tamping rod. The top surface was covered with a steel plate to apply the pressure. This whole procedure of RAC brick casting is shown in Figure 3.

As indicated in Figure 3, the prepared specimens were then placed in machine to apply required pressure. A steel plate was placed on the top of the mold to apply uniform pressure on the specimens. The load was gradually increased to reach the required pressure for each composition and was sustained for 30 seconds. After applying the pressure, specimens were demolded and were placed in open atmosphere for air drying. After one day of air drying, specimens were placed in the water curing tanks for 28-days. To find physical and mechanical properties of concrete bricks, at least three specimens were prepared for each composition and tested.

Table 2. Composition of concrete mixes.

Sr. No.	Mix designation	Cement (%)*	w/c ratio	Pressure applied (MPa)	Superplasticizer
1	RAC-70C30F	15	0.35	25	1% by weight of cement
2	RAC-60C40F	10	0.50	35	
3	NAC-70C30F	15	0.35	25	
4	NAC-60C40F	10	0.50	35	

* by weight of total aggregates (fine and coarse)

Figure 3. Production process of bricks by CCT.

2.4. *Testing procedures*

Concrete bricks prepared with RAC and NAC mixes were tested under various modes of loading. To compare the performance of RAC and NAC bricks with conventional burnt clay bricks, commercially available first class local burnt clay bricks were also tested under similar conditions. The procedure of each test performed is given in the following section.

2.4.1 Compressive strength test

Compressive strength tests were conducted on bricks in accordance with ASTM C67 (ASTM C67). The Denison compression testing machine having loading capacity of 3000 kN was used to perform compression test. Compression loading was applied on brick as shown in Figure 4(a). As mentioned earlier, three samples of each composition were tested, and the average value of compressive strength is reported in this paper.

2.4.2 Flexural strength test

Three point-bending tests under monotonic loading were carried out to determine the flexural strength of the bricks of different compositions. The tests were conducted in accordance with ASTM C67 (ASTM C67) and the testing setup is shown in Figure 4(b). Shimadzu Universal Testing Machine (UTM) with loading rate of 0.5 mm/min was used to perform displacement-controlled flexural strength test. The maximum load at which the flexural crack occurred, and the load value was dropped suddenly was noted and thereafter used to calculate flexural strength.

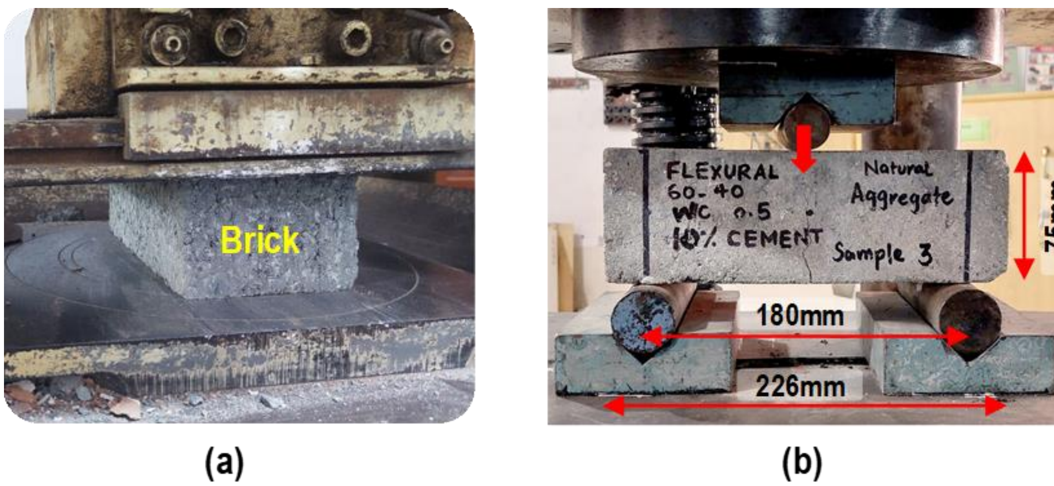


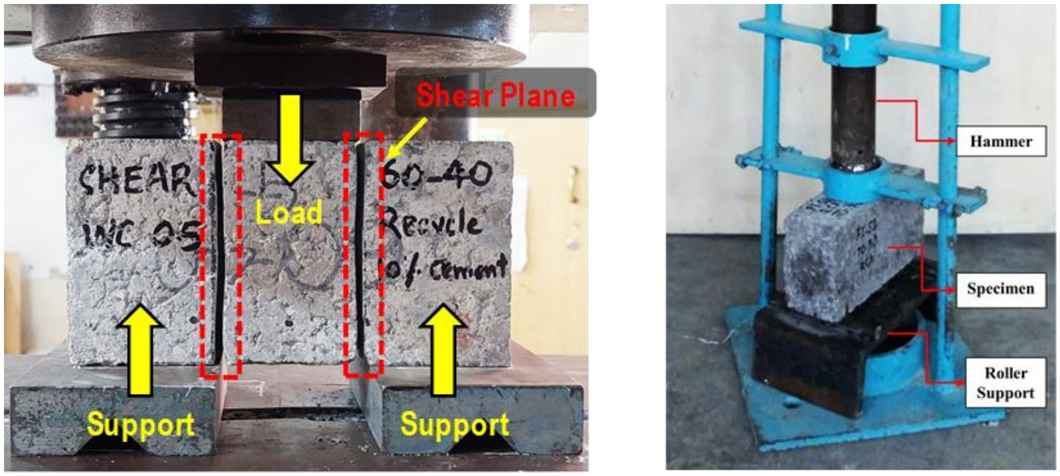
Figure 4. Testing setup; (a) compression test (b) flexural test.

2.4.3 Shear strength test

Shear strength tests on the bricks were performed following the procedure adopted by De Lima et al. (2014). The specimens were notched by saw cutters at two locations on all four sides to induce the intended shear failure plane as shown in Figure 5a. Support was provided at 76 mm from both sides. The displacement-controlled shear strength tests were performed on Universal Testing Machine (UTM) at loading rate of 0.5 mm/min. The load at which the crack occurred in the notched locations was noted to determine the shear strength of brick sample.

2.4.4 Flexural impact test

In order to study the effect of lateral impact load on the brick wall, flexural impact tests on the brick specimens were conducted as per the procedure followed Thakur et al. (2022). The rollers supports were provided on both sides, as shown in Figure 5b and then flexural impact load was applied at the center of side of brick of dimension 75 mm x 226 mm. For flexural impact test, a hammer of weight 10 pounds and height 18 inch was used. Number of blows imparted by the hammer for initial and final crack were counted. Energy at initial and final crack development was calculated from the counted blows, further, the energy absorbed between these two stages was also calculated.



(a) (b)

Figure 5. Testing setup; (a) shear test (b) flexural impact test.

2.4.5 Impact test

To determine the energy absorbed by the bricks under impact load in compression, tests were conducted in accordance with standard EN 60068-2-75 (EN 60068, 2014). To prepare the specimens for this test, 113 mm diameter cores were extracted from the brick specimens. These cores were then subjected to impact load which was applied with the help of same hammer as used for flexural impact test. A steel ball was placed on the top of specimen to apply the load as point load at center. After counting the number of blows up to failure of brick core, the energy was calculated using Equation (1).

$$\boldsymbol{E} = N \times mgh \quad (1)$$

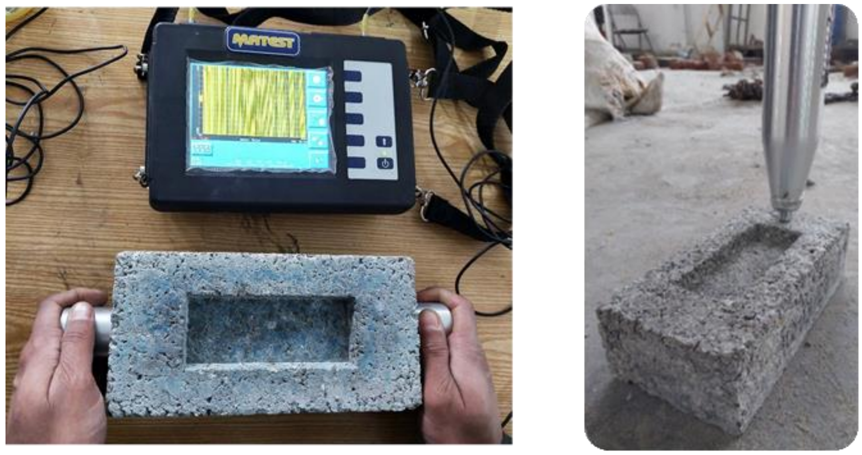
where,
E = energy absorbed by the specimen (J)
N = number of blows at which final crack appeared
m = mass of hammer (kg)
g = gravitational acceleration (ms^{-2})
h = height of fall (m)

2.4.6 Ultrasonic pulse velocity (UPV) test

The UPV tests were performed on all concrete bricks by following the standard ASTM C597 to check their quality. The standard UPV apparatus is shown in Figure 6a. Direct method was adopted i.e.; transmitter and receiver were kept 180º apart. The time of travel between the transmitter and receiver was noted and velocity was calculated. High value of time means low velocity and it indicates more voids. The velocity calculated was then used to rate the quality of concrete specimen as per the guideline provided in ASTM C597-16 for concrete.

2.4.7 Rebound hammer test

Rebound hammer test is a non-destructive test (NDT) which is generally used to get an idea about the uniformity in compressive strength of concrete specimens. In this study, this test was conducted on brick samples in accordance with ASTM C805. The specimens were placed on an even surface and the rebound hammer test was performed as shown in Figure 6b. Six readings of rebound number were taken on each brick sample three on top and bottom surface and then compressive strength was determined based on average value of rebound number using standard charts available with rebound hammer.



(a) (b)

Figure 6. Testing setup: (a) UPV test (b) Rebound hammer test.

3. Results and discussions

For the purpose of comparison, conventional burnt clay bricks were also tested under the same modes of loading and results are presented along with strength values of RAC and NAC bricks.

3.1. Compressive strength

The compressive strength values of all types of bricks prepared and tested in this study are plotted and shown in Figure 7 where it may be observed that NAC bricks showed higher strength compared to RAC bricks which is in line with the literature (Contreras-Llanes et al., 2021; Guo et al., 2018). This reduction in the compressive strength is mainly due to the adhered weak cement mortar with coarse aggregates and porous nature of RAC bricks. NAC-70C30F bricks exhibited 29.7% more compressive strength as compared to RAC-70C30F bricks while NAC-60C40F bricks exhibited 30.9% more compressive strength in comparison of RAC-60C40F bricks. Among two different mix ratios investigated in this study, a mix containing 70% coarse aggregates and 30% fine aggregates attained higher compressive strength even though the coarse aggregates are more porous (Hameed et al., 2022). This increase in the compressive strength might be attributed to the higher cement content which results in the denser microstructure and the effect of higher dosage of cement can be seen from the results presented in Figure 2. The compressive strength of RAC-70C30F bricks was 21.1% more than RAC-60C40F bricks, similarly compressive strength of NAC-70C30F bricks was 20% more than NAC-60C40F bricks. Although casting pressure was higher for mix 60C40F, but compressive strength was lesser than mix 70C30F, this observation highlighted the importance of determining casting pressure for a particular mix to get maximum compressive strength. It is further observed in Figure 7 that RAC bricks exhibited compressive strength higher than locally available first class burnt clay bricks. Use of RAC bricks of higher strength in place of burnt clay bricks would not only ensure sustainability but also will help to reduce the required wall thickness to carry certain gravity loads.

3.2. Flexural strength

Figure 8 shows the values of flexural strength of the bricks made with various compositions which was calculated based on maximum failure load of each brick. From these results, it was observed that all tested bricks exhibited flexural strength more than the standard value of 1.96 MPa which is generally required for masonry works. The flexural strength of RAC-60C40F bricks was 3.11 MPa which was 5.1% higher than RAC-70C30F bricks because of the higher content of RFA due to which denser microstructure was developed. The flexural strength exhibited by clay bricks was 3.21 MPa which was 3.1% higher than RAC-60C40F. The flexural strength obtained by RAC bricks was lesser than the NAC because of the weaker interfacial transition zone (ITZ) between RA and binder (Ozbakkaloglu et al., 2018). The flexural strength of NAC-60C40F was 37.3% higher than RAC-60C40F bricks while NAC-70C30F bricks attained 20.7% higher flexural strength than RAC-60C40F bricks. Typical failure modes of concrete and burnt clay bricks are shown in Figure 9. It was observed during testing that burnt clay bricks showed highly brittle failure while in case of both RAC and NAC bricks, with the application of load, crack started at the bottom and gradually propagated upward, and load value was suddenly dropped when cracked passed through out the depth of brick.

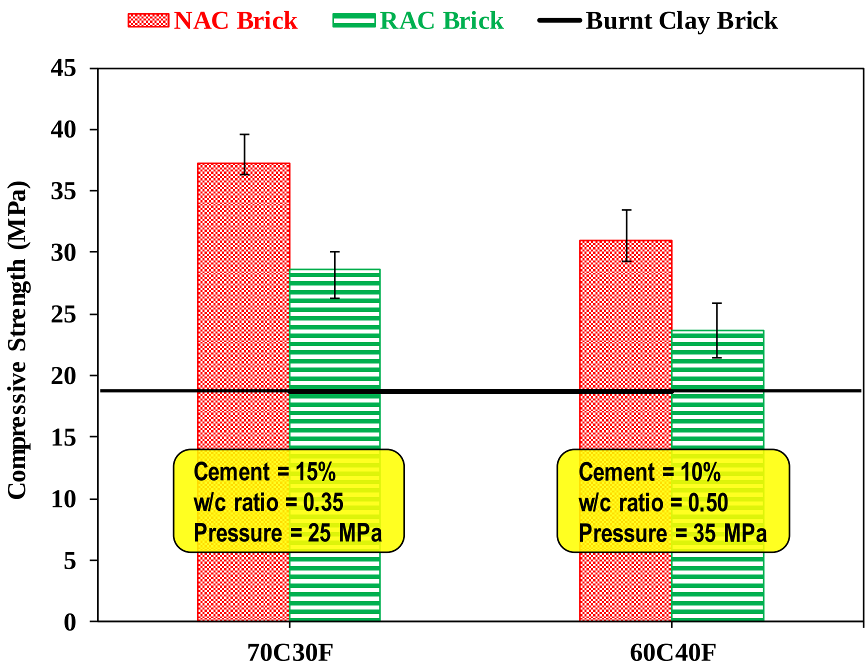


Figure 7. Compressive strength of bricks.

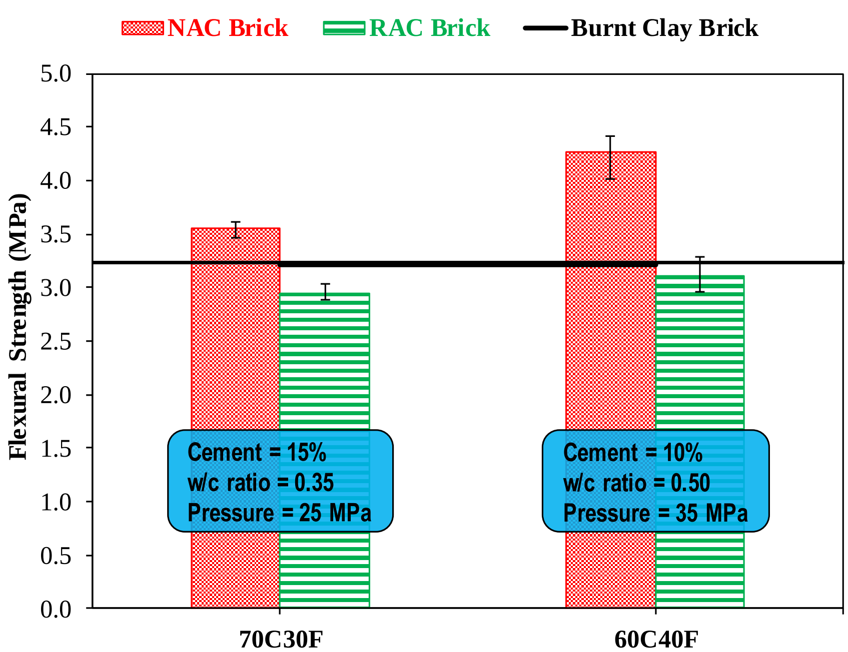


Figure 8. Flexural strength of bricks.

Figure 9. Failure modes of bricks under three-point bending test (a) RAC-70C30F brick (b) RAC-60C40F brick (c) NAC-70C30F brick (d) NAC-60C40F brick (e) Burnt clay brick.

3.3. Shear strength

Shear strength was calculated by using the maximum load attained in shear test and area of contact at two shear failure planes which was determined after failure of the specimen because groove which was made in each brick with the help of concrete cutter to predefine the failure path was not of same size in each brick. The results presented in Figure 10 showed that the shear strength of NAC bricks was more than the RAC bricks. Bricks of both mixes of NAC showed almost the same shear strength. Lower shear strength for RAC bricks is mainly attributed to two weaker ITZ (Otsuki et al., 2003). The first ITZ is between the original aggregates and adhesive mortar (old ITZ) and the second one is between the adhesive mortar and new mortar mix in RAC bricks (new ITZ). NAC-70C30F bricks had 31.2% more strength as compared to RAC-70C30F bricks while NAC-60C40F bricks exhibited 81.3% more strength as compared to RAC-60C40F bricks. Burnt clay bricks attained shear strength of 3.0 MPa which was 62.2% of the least shear strength (i.e., 4.82 MPa) attained by concrete bricks manufactured using RAC-60C40F mix. Typical failure mode in shear observed in each type of brick has been shown in Figure 11.

3.4. Flexural impact test

The results reported in Figure 12 showed that the flexural impact energy (FIE) of RAC bricks was lower than NAC bricks due to the variations in the quality and strength of recycled aggregates as compared to natural aggregates (Hameed et al., 2022, Hamad et al., 2017). Among different bricks tested in this study, burnt clay bricks exhibited minimum value of FIE. It is very clear in the failure modes shown in Figure 13 that in case of RAC bricks and burnt clay bricks, failure path was vertically straight, and examination of failure surface of RAC bricks indicated that crack travelled through most of the coarse aggregates. However, in case of NAC bricks, crack path was not vertically straight, and travel length was more as compared to RAC bricks. Study of failure surface NAC bricks indicated that failure occurred in cement matrix and through ITZ which resulted in higher value of FIE with these bricks. Further, it is clear from the results presented in Figure 12 that presence of high content of coarse aggregates and cement in NAC-70C30F bricks also caused enhancement in FIE value compared to NAC-60C40F bricks. On the contrary, due to weaker recycled aggregates, both mixes of RAC bricks attained almost the same value of FIE.

Quantitative assessment of FIE values indicated that NAC-70C30F bricks absorbed 11% more energy compared to NAC-60C40F bricks. Energy absorbed by RAC bricks (both mix ratios) was 40% and 45% of the value exhibited by NAC-70C30F bricks and NAC-60C40F bricks, respectively. However, FIE of RAC bricks was 71% more as compared to burnt clay bricks.

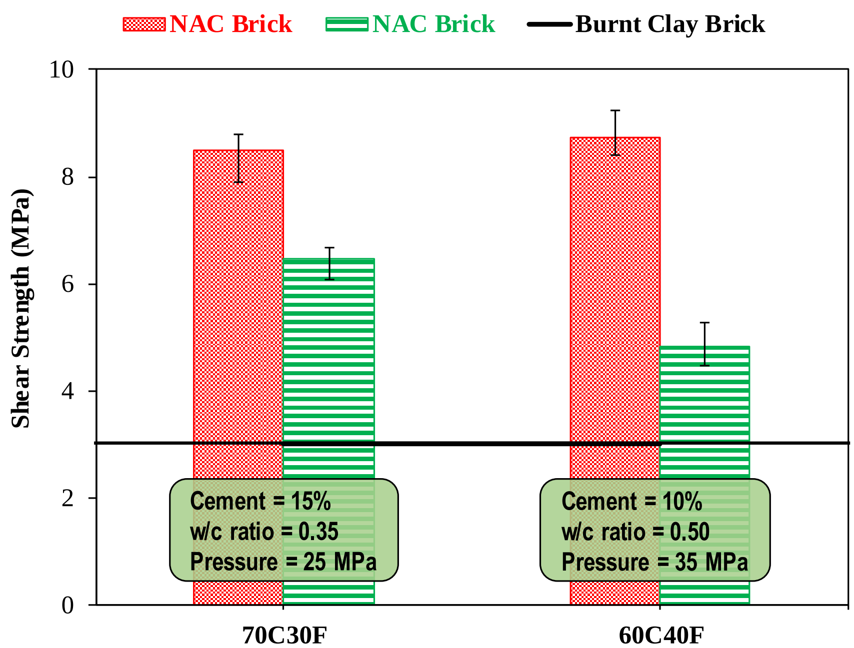


Figure 10. Shear strength of bricks

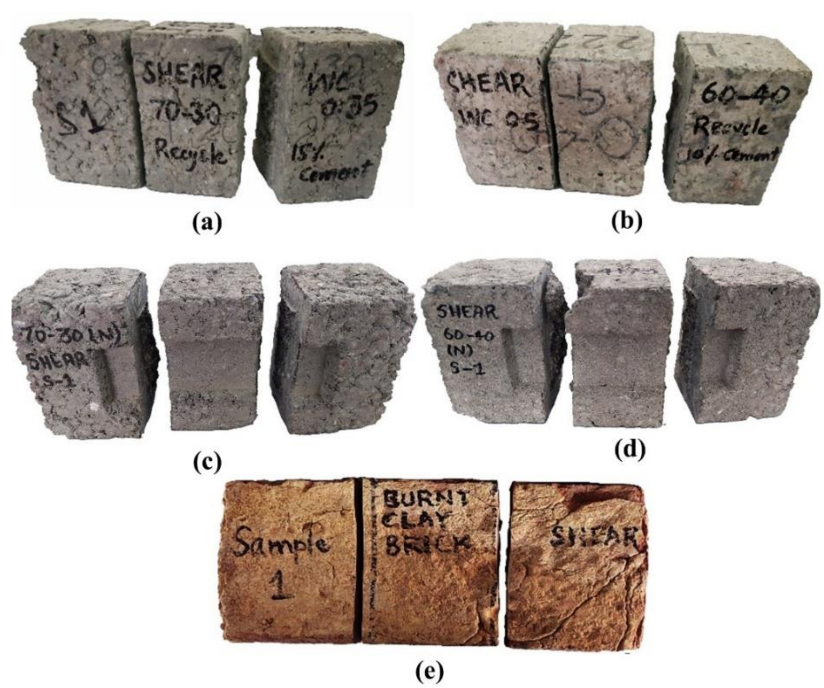


Figure 11. Failure mode of bricks in shear (a) RAC-70C30F brick (b) RAC-60C40F brick (c) NAC-70C30F brick (d) NAC-60C40F brick (e) Burnt clay brick

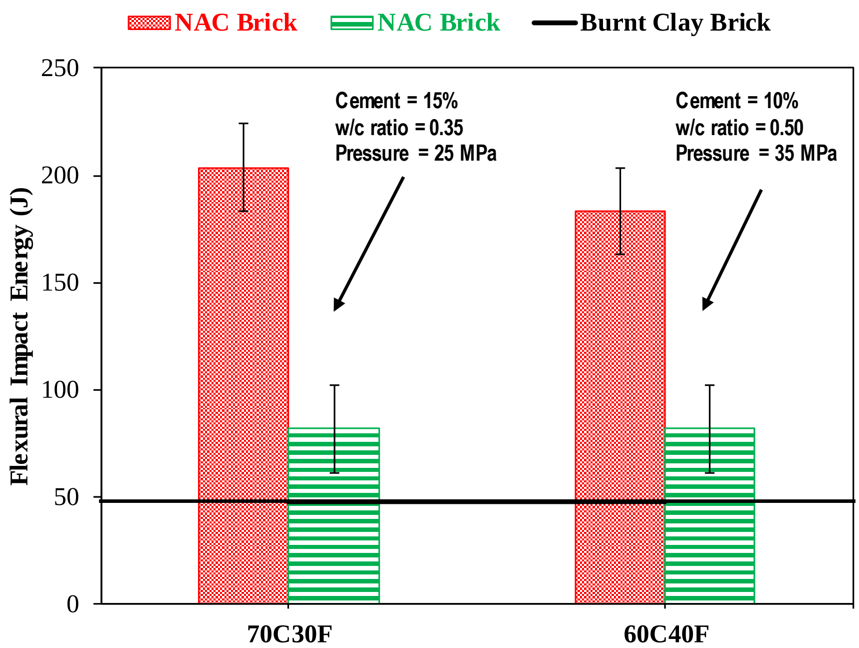


Figure 12. Flexural impact energy of bricks.

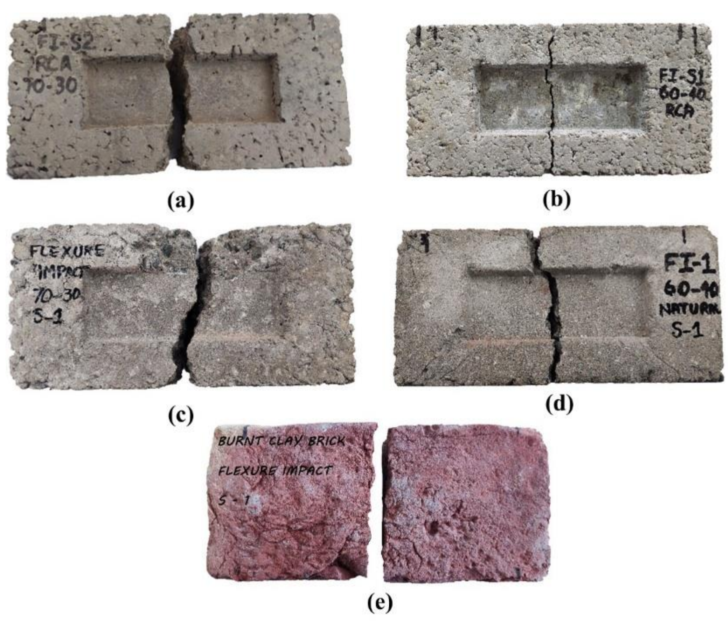


Figure 13. Failure modes of bricks in flexural impact test (a) RAC-70C30F brick (b) RAC-60C40F brick (c) NAC-70C30F brick (d) NAC-60C40F brick (e) Burnt clay brick.

3.5. Impact test

The results of impact test in compression performed on disc samples extracted from bricks are presented in Figure 14 where the response is similar to flexural impact energy, impact energy of RAC bricks was lesser than NAC bricks and both mixes of RAC bricks showed almost same value of impact energy. However, contrary to flexural impact energy, mix of NAC containing 60% coarse aggregates and 40% fine aggregates absorbed more impact energy as compared to mix NAC-70C30F, this indicates that in case of impact energy in compression, presence of more fine aggregates in the mix is beneficial. In this study, NAC-60C40F bricks achieved the maximum impact energy of 142.5 J which was 55.5% more than RAC-60C40F bricks while these bricks (RAC-60C40F) absorbed 22.2% higher impact energy as compared to burnt clay brick. Typical failure mode in impact shown by disc samples extracted from each type of brick tested in this study has been shown in Figure 15 where it can be noticed that fan-like failure was the dominant mode of failure in most of the cases.

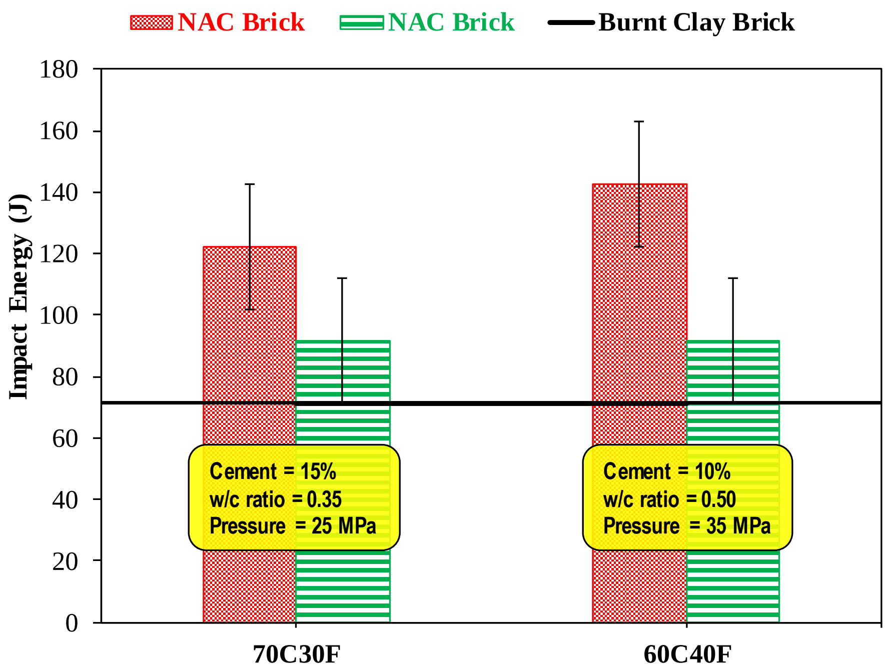


Figure 14. Impact energy of concrete and clay bricks

3.6. Ultrasonic pulse velocity test

The results obtained from UPV test have been presented in Table 3 for various types of brick tested in this study. It may be observed from these results that RAC bricks had lower value of velocity as compared to NAC bricks because of their more porous nature (Gómez-Soberón, 2002). However, both compositions of RAC bricks fall in "Good" category as per the criteria proposed in standard document IS 13311-1 (IS Standard, 1992) indicating that the internal structure of concrete was of good quality and can be used in masonry construction. The results showed that with the increase of coarse aggregate and cement contents in case of "70C30F" mixes of RAC and NAC, velocity was increased indicating better internal micro-structure although casting pressure was less compared to "60C40F" mixes.

3.7. Rebound hammer test

The compressive strength of bricks measured by rebound hammer test as non-destructive test (NDT) is shown in Figure 16 along with strength values determined by destructive test (DT). It is obvious from these results that the compressive strength determined by NDT [i.e., Rebound Hammer Test] was slower than DT values. Compressive strength by NDT of RAC-60C40F bricks, RAC-70C30F bricks, NAC-60C40F bricks and NAC-70C30F bricks was found to be 70%, 58%, 44% and 40% of their DT values, respectively. Based on the results of this study, on average, a factor of 1.58 and 2.38 may be used to determine compressive strength of RAC and NAC bricks, respectively from compressive strength determined by Rebound Hammer test. Such NDT type and correlation factor between DT & NDT strength could be considered a good tool for felid usage in order to get an idea regarding the load carrying capacity of RAC bricks and to make decision regarding their acceptance or rejection for a particular project.

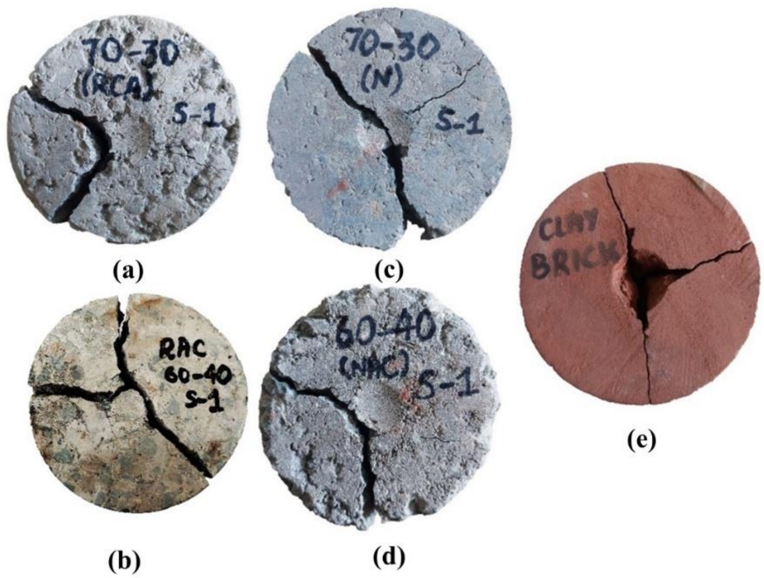


Figure 15. Failure mode of bricks under impact test (a) RAC-70C30F brick (b) RAC-60C40F brick (c) NAC-70C30F brick (d) NAC-60C40F brick (e) Burnt clay brick.

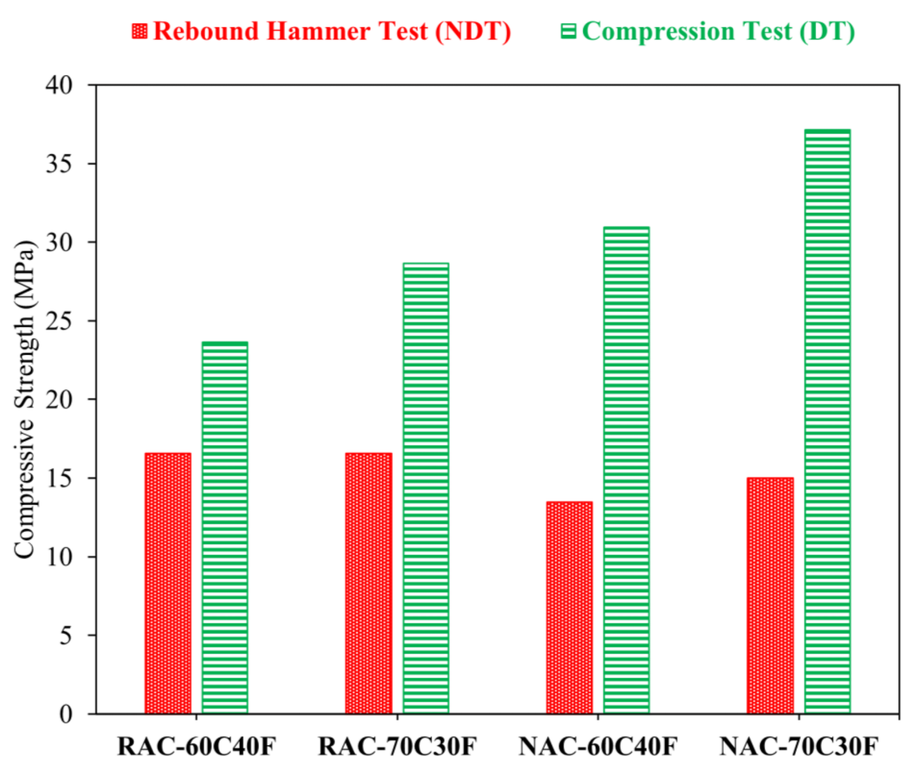


Figure 16. Compressive strength of bricks.

Table 3. Ultrasonic pulse velocity (UPV) test results.

Designation	Sample	UPV test results			Remark
		Time (µs)	Distance (m)	Velocity (m/s)	
RAC-60C40F	1	56.1	0.23	4075	Good
	2	59.5	0.23	3842	Good
	3	56.1	0.23	4075	Good
	Average velocity			3771	Good
RAC-70C30F	1	56.6	0.23	4039	Good
	2	61.2	0.23	3735	Good
	3	56.1	0.23	4075	Good
	Average velocity			3860	Good
NAC-60C40F	1	54.5	0.23	4194	Good
	2	54.5	0.23	4194	Good
	3	53.3	0.23	4289	Good
	Average velocity			4252	Good
NAC-70C30F	1	52.4	0.23	4363	Good
	2	49.8	0.23	4590	Excellent
	3	51.9	0.23	4405	Good
	Average velocity			4400	Good

Based on the results, it was observed that the performance of NAC bricks was better than RAC bricks. In the case of RAC, the presence of old ITZ due to the adhered mortar to aggregates and higher porosity of recycled aggregates (as evident from their water absorption values presented in Table 1) results in detrimental effect on the strength properties of RAC bricks. However, in comparison to conventionally used burnt clay bricks, RAC bricks showed better performance in terms of strength. Since the mechanical performance of RAC bricks prepared by compression casting in this study has been found to be better than burnt clay bricks and fulfilling the minimum strength requirements, use of such bricks in construction will result in less demand of burnt clay bricks which will ultimately lead to conservation of natural resources of clay. Further, pollution caused by burning of coal in the brick kiln as fuel will also be reduced. Moreover, use of recycled concrete aggregates will not only help in effective management of C&D waste but will also result in economical concrete products. Ultimately, through this whole process, sustainability in construction industry could be ensured.

4. Cost Comparison

As per local rate of materials used to manufacture burnt clay bricks, NAC bricks and RAC bricks in this study, cost comparison was made. It was found that manufacturing cost of RAC brick was 35% and 19% less than the cost of burnt-clay bricks and NAC bricks, respectively.

5. Conclusions

The main objective of this study was to study the mechanical performance of 100% RAC bricks to provide a sustainable solution by the effective utilization of C&D waste. Various tests such as compression, flexural, flexural impact, impact and UPV were performed on the 100% RAC bricks and the same were compared with corresponding results of 100% NAC bricks. Based on experimental results obtained in this study, following conclusions have been drawn:

1. 100% RAC bricks passed all the standard limits for compressive strength, shear strength and flexure strength as per local and international standards.
2. With respect to fine to coarse aggregate ratio, cement content and casting pressure used in this study, for both RAC and NAC bricks, compressive and shear strengths of mix 70C30F were higher than that of mix 60C40F because of greater percentage of coarse aggregates. RAC bricks prepared with 70:30 ratio of coarse to fine aggregates showed 21.1% higher compressive strength than the RAC bricks prepared with 60:40 ratio.
3. The compressive strength of NAC bricks was about 30% higher than the RAC bricks. However, RAC-70C30F bricks and RAC-60C40F bricks exhibited 53% and 26% higher compressive strength as compared to the locally available first class burnt-clay bricks, respectively.
4. The flexural strength of RAC-60C40F and RAC-70C30F bricks was found to be almost similar. However, their flexure strength was 37.3% and 20.7% lesser than the corresponding NAC bricks. A difference of 2 to 8% in the flexure strength of RAC bricks and burnt clay bricks was found.
5. For both RAC and NAC bricks prepared in this study, qualitative assessment by ultrasonic pulse velocity (UPV) tests declared both types of bricks of good quality.
6. The rebound hammer test underestimated the compressive strength of concrete bricks. However, the difference in NDT and DT values for RAC bricks was smaller than for NAC bricks. A correlation of 1.58 and 2.38 has been proposed between NDT & DT values for RAC and NAC bricks, respectively.
7. The quantity of fine and coarse aggregates showed its influence on the impact energy absorbed by the bricks in compression and flexure. For flexural impact, higher content of coarse aggregates in the mix showed positive impact on the impact energy absorbed while less content of coarse aggregates appeared to be beneficial in case of impact energy in compression.
8. 100% RAC bricks were found to be an efficient, eco-friendly and economical alternative to burnt clay bricks as they are able to fulfill the strength requirements.
9. Use of 100% RAC bricks in residential buildings will not only conserve the depleting natural resources of aggregates and clay but also help to protect environment from pollution.

It is pertinent to mention here that the results presented in this study are related to RAC bricks made using RCA produced from parent concrete of compressive strength in the range of 21 MPa to 28 MPa. RCA produced from other concrete strength will have different impact on the mechanical performance of RAC bricks. Future study in the continuation of present work by the authors will focus on studying the impact of parent concrete strength and evaluation of durability performance of 100% RAC bricks. Regarding the recommendation of future study in this area, use of supplementary cementitious materials such as fly ash and natural pozzolana may be used to further reduce the quantity of cement.

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