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# Impact of Compression Casting Technique on the Mechanical Properties of 100% Recycled Aggregate Concrete

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**Abstract:** The research work presented in this manuscript focused on the comparative examination of the influence of the Compression Casting Technique (CCT) and the conventional casting method (i.e., compaction through vibration) on the performance of 100% Recycled Aggregate Concrete (RAC). The minimum target compressive strength of 100% RAC was 15 MPa keeping in view its application in the manufacturing of load-bearing concrete masonry units. A total of 28 concrete compositions were prepared by varying the coarse to fine aggregates ratio (i.e., 70:30 and 60:40), cement content (10% and 15%) by weight of total aggregates, casting technique, and applied pressure for compression casting (i.e., 25, 35, and 45 MPa). The concrete compositions were tested to determine their density, compressive strength, Elastic Modulus (EM), and Ultrasonic Pulse Velocity (UPV). For comparison, samples of Natural Aggregate Concrete (NAC) were also tested for the same properties. The results highlighted the positive impact of CCT on the properties of 100% RAC. The compressive strength and EM of fully RAC was increased by 20–80% and 15–50%, respectively, by changing casting method from vibration to CCT. At casting pressure of 35 MPa and 15% cement, compressed 100% RAC exhibited compressive strength higher than vibrated NAC. The UPV value exhibited by 100% RAC was increased by changing the casting technique. The analytical models were proposed using regression analysis of experimental results to predict compressive strength and EM of compressed 100% RAC and NAC. These proposed models were evaluated using statistical parameters, i.e., average absolute error (AAE) and mean (M) and found to be able to predict the compressive strength and EM of RAC with reasonable accuracy as compared to the analytical models already existing in the literature. This study finally concluded that through CCT, 100% RAC with low cement content could achieve minimum target compressive strength of 15 MPa. The development and use of compressed load-bearing 100% RAC construction units would help to achieve sustainability in construction.

**Keywords:** recycled aggregate concrete; casting technique; mechanical performance; analytical models; sustainability



**Citation:** Hameed, R.; Tahir, M.; Zaib-un-Nisa; Shahzad, S.; Kazmi, S.M.S.; Munir, M.J. Impact of Compression Casting Technique on the Mechanical Properties of 100% Recycled Aggregate Concrete. *Sustainability* **2023**, *15*, 8153. https://doi.org/10.3390/su15108153

Academic Editor: José Ignacio Alvarez

Received: 22 April 2023
Revised: 8 May 2023
Accepted: 15 May 2023
Published: 17 May 2023



## 1. Introduction

Concrete is one of the most used construction materials [1] with annual consumption reaching an all-time high of 10 billion $m^3$ [2] around the globe. Due to the several advantages this material offers as compared to the other competitors [3] and the development going on around the globe, concrete production is further expected to increase in the coming decades. This increasing trend in concrete production warrants an increase in the demand for aggregates which constitute almost 75% of the total volume of concrete [4,5]. An estimate shows the consumption of 48.3 billion tons of natural aggregates worldwide annually, and it is expected that this demand will be increased two times in the next two to three decades [6]. Along with the increasing demand for concrete constituents for producing new concrete, there is another issue of the generation of a large volume of waste concrete [4]. This waste concrete is being produced either from the demolition of existing infrastructure which has reached its design life, or which is damaged due to natural disasters. Further, the restructuring or up-gradation plans of existing structures due to the rapid infrastructure development and urbanization of the 21st century are the other major sources of waste concrete [5]. Effective disposal of waste concrete has become a serious concern due to the environmental threats that it poses and the increased demand for landfills. Both of the above-mentioned issues need to be tackled effectively to manage the infrastructure needs of future generations while preserving the natural resources of aggregates and protecting the environment, hence making the concrete more sustainable.

Recycling waste concrete as the source of Recycled Aggregates (RA) and their use in new concrete provides a single solution to both the problems of increasing demand for natural aggregates and the issues related to the disposal of waste concrete, and it has been studied by several researchers over the past few decades [7–15]. However, the research on the incorporation of recycled concrete aggregates in concrete shows, in general, a negative impact on both the mechanical and durability properties of the resulting concrete. This is due to the higher porosity of recycled aggregates resulting from the presence of mortar particles in RA and a weaker interfacial transition zone (ITZ) between RA and cement paste in new concrete due to the mortar attached to RA [4–12,16]. To counter this problem, researchers have proposed two basic solutions based on their extensive experimentation. The first solution is to improve the RA by involving several techniques [17] such as mechanical treatment [18], pre-soaking in acidic solution [19], thermo-mechanical treatment [20,21], and different surface treatments such as carbonation [22], soaking in sodium silicate [23] or nano-silica [24]. However, these techniques are generally not energy and cost-efficient or environment-friendly [5,17]. The second solution proposed by the researcher is to limit the percentage of replacement of Natural Aggregates (NA) by RA or an increased dosage of cement to obtain an acceptable level of mechanical and durability performance.

A detailed review of the literature [25] showed that most of the past studies related to the recycling of concrete as aggregates deal with only recycled coarse aggregates (RCA). There is still hesitation in the use of recycled fine aggregates (RFA) in concrete [26] mainly because of an increased negative impact on the properties of the resulting concrete which is due to the higher amount of residual cement and attached mortar in RFA as compared to RCA. Increased use of RFA in Recycled Aggregate Concrete (RAC) leads to higher cement demand for achieving the same target strength of concrete. Therefore, the recommended dosage of RFA has been limited to 20 to 30% of the total fine aggregates volume [27,28]. However, RFA and RCA are produced in almost equal proportions during the recycling process, i.e., about 50% of the volume of crushed material is the fraction having a maximum particle size of 4 mm [27]. However, recently there is an increased focus of research on the incorporation of RFA in concrete [25,29–34], and fewer studies have investigated the RAC with 100% recycled aggregates (both RFA and RCA) [26,35]. Therefore, there is a need to investigate ways to efficiently incorporate the fine fraction of the recycled concrete in the design of sustainable concrete.

One of the factors which affects the properties of concrete is the casting methodology. The conventional casting methodology, i.e., compacting through vibrations during casting, results in an increased cement requirement to achieve the same target strength of RAC as compared to Natural Aggregate Concrete (NAC) [36]. To overcome this requirement, several researchers have been proposing the use of the compression casting technique (CCT), especially in the precast industry. It improves the packing of concrete, reduces the porosity, and hence increases both the mechanical and durability performance of the resulting RAC with a reduced cement consumption [16,37–41]. In one such study, the effect of CCT, nano silica, and their combination for improving the RAC was investigated by Liang et al. [16]. Both macro- and micro-level examinations of the resulting RAC were conducted. It was concluded that the CCT can be effectively used to reduce the total porosity of the RAC and the pore ratio along the ITZ. The effectiveness of CCT for improving concrete was also shown by Wu et al. [42] for rubberized concrete. They found an improved stress–strain behavior of rubberized concrete due to the application of CCT and concluded that through CCT, the same mechanical properties as those of uncompressed NAC can be achieved for the concrete containing 30% rubber aggregates in replacement to NCA.

This study focused on tackling the issues related to the incorporation of 100% RA (fine and coarse) in concrete by taking advantage of the CCT. RAC containing 100% RA is prepared for a target strength of 15 MPa, and the effect of casting pressure, cement dosage, and the ratio of fine to coarse fraction of RA on the physical and mechanical properties of the resulting RAC is investigated. The results are compared with the specimens prepared using the conventional vibration approach to demonstrate the effectiveness of CCT. A target strength of 15 MPa was selected as this satisfies the minimum strength requirement of most of the standards related to masonry units [43].

The main focus of this study is to make the concrete recycling process eco-efficient and sustainable by investigating the possibility of developing RAC containing 100% RA by the combined use of RFA and RCA. The literature review indicated that there is a lack of research on the use of 100% RA (RCA and RFA) for the production of new concrete; either more of the research focus was on the use of RCA in RAC, or it focused on the separate investigation of RCA and RFA incorporation because of the durability issues associated with RA. The latest research studies [39,40] prove the potential use of CCT for improving the RAC; however, there is a paucity of research on its utilization for developing concrete containing 100% RA with the minimal use of cement. Furthermore, there is no study showing the effect of varying pressure levels of CCT and the mix ratio of RFA and RCA on the properties of RAC. Hence, this study investigates the effect of varying casting pressure, mix ratio of recycled aggregates and cement content on the mechanical properties of resulting concrete with an aim to develop 15 MPa strength of concrete having 100% RA, for its possible utilization in the precast industry to make eco-friendly masonry units. Currently, 82.5 billion burnt clay bricks are being produced in Pakistan annually from more than 18,000 brick kilns [44], and the brick manufacturing industry is causing serious environmental and health issues and air pollution resulting in smog, particularly in winter [45,46]. The findings of this study could be helpful in solving such issues by introducing an eco-friendly material option for the manufacturing of concrete masonry units (bricks) as an alternative to burnt clay bricks.

## 2. Materials and Methods

### *2.1. Materials*

Laboratory-tested (crushed) concrete cubes and cylinders (refer to Figure 1) having compressive strength in the range of 21 to 28 MPa were collected and passed through jaw and roller crushers to produce RA of maximum 12 mm size. The process of RA production is shown in Figure 2. Selected physical and mechanical tests such as bulk density, water absorption, abrasion resistance, and impact value tests were performed on fine and coarse aggregates following ASTM/BS standards to characterize them. The results of these tests have been presented in Table 1. The gradation curves for RFA and RCA are plotted as shown in Figure 3A,B, which indicates that both RA meet the gradation criteria prescribed in ASTM C33 [47]. The bulk density and specific gravity of RA are lesser than that of NA, while the abrasion value and water absorption are higher.

For this study, river sand and crushed stones were used as Natural Fine Aggregates (NFA) and Natural Coarse Aggregates (NCA), respectively. The properties of NFA and NCA are given in Table 1. Gradation curves of NCA and NFA are shown in Figure 3C,D, respectively, indicating that both aggregates satisfy the grading criteria given in ASTM C33. To prepare all concrete compositions, Ordinary Portland cement in conformance with ASTM C150 [48] was used. The chemical composition and physical properties of the cement are provided in Tables 2 and 3, respectively.

**Figure 1.** Crushed samples of concrete as source of RA.


**Figure 2.** Process of production of recycled concrete aggregates.

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

| Property | RA | | NA | |
|---|---|---|---|---|
| | Coarse | Fine | Coarse | Fine |
| Bulk oven dry Specific Gravity | 2.26 | 2.05 | 2.84 | 2.70 |
| Bulk SSD Specific Gravity | 2.44 | 2.28 | 2.86 | 2.75 |
| Bulk Apparent Specific Gravity | 2.76 | 2.66 | 2.87 | 2.84 |
| Water Absorption (%) | 7.97 | 11.15 | 0.9 | 1.79 |
| Moisture Content (%) | 2.37 | 5.32 | 0.9 | 1.2 |
| Flakiness Index (%) | 14.1 | - | 19.6 | - |
| Elongation Index (%) | 21.25 | - | 44.1 | - |
| Bulk Density (kg/m$^3$) | 1267 | 1335 | 1441 | 1722 |
| Los Angeles Abrasion Value (%) | 37.57 | - | 25.20 | |
| 10% Fine Value, TFV (kN) | 184.36 | - | 199.57 | |
| Aggregate Crushing Value, ACV (%) | 20.80 | - | 22.55 | |
| Aggregate Impact Value, AIV (%) | 15.36 | - | 17.70 | |

**Table 2.** Chemical composition of cement.

| Chemical Composition | CaO | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MgO | $SO_3$ |
|---|---|---|---|---|---|---|
| | 62.6% | 20.8% | 5.06% | 3.27% | 2.56% | 1.57% |

**Table 3.** Physical properties of cement.

| Physical Properties | Fineness | Soundness | Initial and Final Setting | Standard Consistency |
|---|---|---|---|---|
| | 8% | 9 mm | 105–215 | 30% |

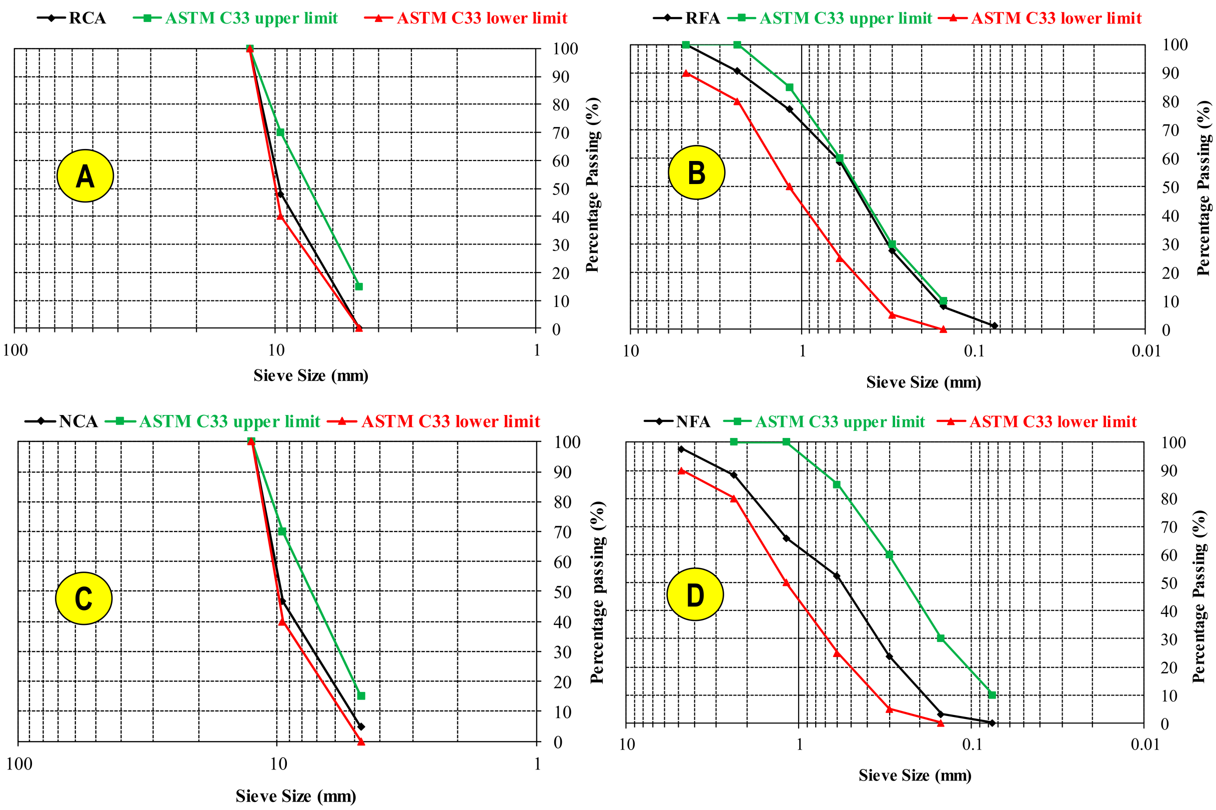



**Figure 3.** Gradation curves of (**A**) RCA, (**B**) RFA, (**C**) NCA, and (**D**) NFA.

## 2.2. Mix Proportions

A total of 28 different concrete compositions were prepared and tested in this study. NCA and RCA were used in Saturated Surface Dry (SSD) condition. In the trial compositions, it was observed that by using RA in dry state and adding the additional amount of water to cater the absorption factor, 28 to 33% of the water added as absorption factor was expelled under applied pressure resulting in reducing the effective w/c ratio (lesser than the required w/c for hydration process) resulting in negative impact on compressive strength. The details of all 28 concrete compositions are given in Table 4. The concrete compositions were designated as RAC, NAC, F, C, and V for recycled aggregate concrete, natural aggregate concrete, fine aggregates, coarse aggregate, and compaction by vibration, respectively. For instance, for RAC-30F70C concrete composition, "RAC" represents recycled aggregate concrete, 30F denotes 30% of fine aggregates, and 70C shows 70% of coarse aggregates.

**Table 4.** Concrete mix proportions.

| Sr. No. | Concrete Designation | Cement Content, % (kg/m$^3$) | Fine Aggregates, kg/m$^3$ | Coarse Aggregates, kg/m$^3$ | Water/Cement Ratio | Applied Pressure, MPa |
|---|---|---|---|---|---|---|
| 1 | RAC-30F70C | 10 (195) | 580 | 1355 | 0.5 | 25 |
| 2 | | | | | | 35 |
| 3 | | | | | | 45 |
| 4 | | 15 (290) | 580 | 1355 | | 25 |
| 5 | | | | | | 35 |
| 6 | | | | | | 45 |
| 7 | RAC-40F60C | 10 (205) | 825 | 1230 | | 25 |
| 8 | | | | | | 35 |
| 9 | | | | | | 45 |
| 10 | | 15 (310) | 825 | 1230 | | 25 |
| 11 | | | | | | 35 |
| 12 | | | | | | 45 |
| 13 | NAC-30F70C | 10 (195) | 580 | 1355 | 0.5 | 25 |
| 14 | | | | | | 35 |
| 15 | | | | | | 45 |
| 16 | | 15 (290) | 580 | 1355 | | 25 |
| 17 | | | | | | 35 |
| 18 | | | | | | 45 |
| 19 | NAC-40F60C | 10 (205) | 825 | 1230 | | 25 |
| 20 | | | | | | 35 |
| 21 | | | | | | 45 |
| 22 | | 15 (310) | 825 | 1230 | | 25 |
| 23 | | | | | | 35 |
| 24 | | | | | | 45 |
| 25 | RAC-30F70C-V | 10 (195) | 580 | 1355 | 0.5 | Compaction by Vibration (Conventional method) |
| 26 | | 15 (290) | 580 | 1355 | | |
| 27 | RAC-40F60C-V | 10 (205) | 825 | 1230 | | |
| 28 | | 15 (310) | 825 | 1230 | | |

## 2.3. Preparation of Specimens

Cylindrical specimens of 150 mm height and 75 mm diameter were cast by CCT and conventional method of casting (i.e., compaction by vibration). For CCT, metallic mold as shown in Figure 4 was prepared which consists of 3 parts. Part 1: a hollow cylindrical tube of height 275 mm and internal diameter 75 mm; Part 2: an end block (to be fixed on one end). In order to avoid development of pore water pressure during casting, small holes were provided in this part at three locations to release the squeezed-out/expelled water due to the applied pressure; Part 3: a plunger which is used to apply pressure on material filled in part 1 of the mold.


**Figure 4.** Metallic mold prepared for compression casting.

After preparation, the concrete was poured in the mold in two layers. To apply required casting pressure on specimen, load was applied through plunger with the help of universal testing machine. The process of sample preparation by CCT is presented in Figure 5. To optimize the value of the casting pressure to be applied, experiments were conducted in which specimens were prepared at various casting pressures varying from 10 MPa to 45 MPa and the corresponding densities were measured. From the results obtained, it was observed that the density of concrete compressed specimen was increased with the increase in casting pressure as shown in Figure 6. Hence, the lower limit of 25 MPa was decided based on the aspects related to sample making, while the upper limit of 45 MPa was decided based on the facts related to infrastructure availability to apply such pressure and field applications. After applying and maintaining casting pressure for 15 s, the sample was extruded from the mold. For the purpose of comparison, samples from each concrete composition were also prepared by the conventional method of casting (i.e., by vibration). Firstly, all samples were air-dried for 24 h and then water-cured for 28 days. After curing of the specimens, they were cut to required height of 150 mm with the help of concrete cutter.

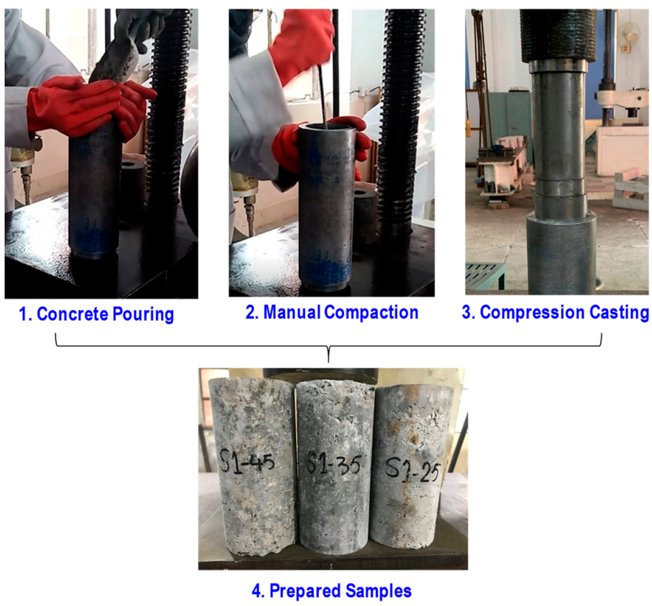



**Figure 5.** Sample preparation under compression casting technique.

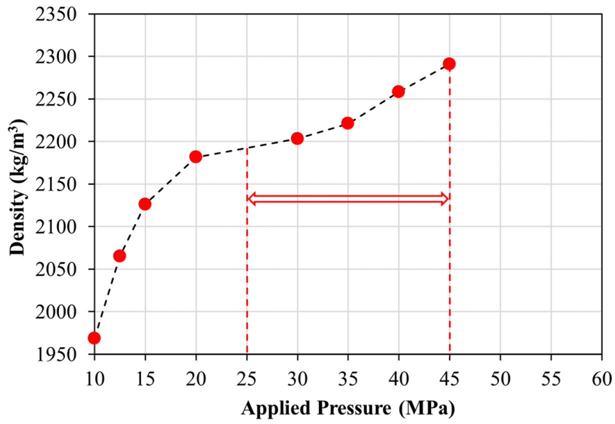



**Figure 6.** Determination of applied pressure for CCT.

### *2.4. Testing Procedures*

In this study, the performance of test specimens made using CCT and conventional compaction technique for different concrete compositions was evaluated based on the four properties, i.e., density, compressive strength, elastic modulus, and ultrasonic pulse velocity. Three specimens of each type of concrete composition were tested and the average result of each property has been reported in this study.

#### 2.4.1. Density

After preparing test specimens using the compression casting technique and conventional method, the weight and length of each sample were determined after 24 h of casting to find the density of concrete. The following relation has been used to calculate the density of each cylinder.

$$\rho = \frac{m}{v}, \quad (1)$$

where $\rho$ is the density of the specimen (kg/m$^3$), $m$ is the mass of specimen (kg), and $v$ is the volume of specimen (m$^3$).

#### 2.4.2. Compressive Strength Test

Compressive strength tests were performed after 28 days of curing of concrete samples in accordance with ASTM C39 [49] specifications. Displacement-controlled compression tests were performed on Universal Testing Machine (UTM) of maximum loading capacity of 1000 kN at a loading rate of 0.5 mm/min as shown in Figure 7.

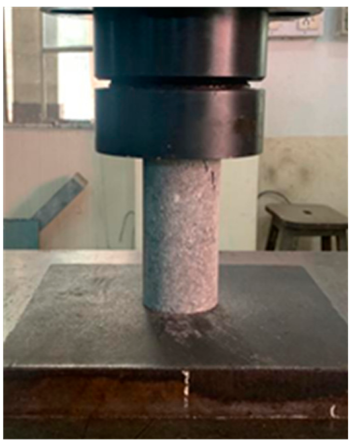


**Figure 7.** Compression test on concrete cylinder.

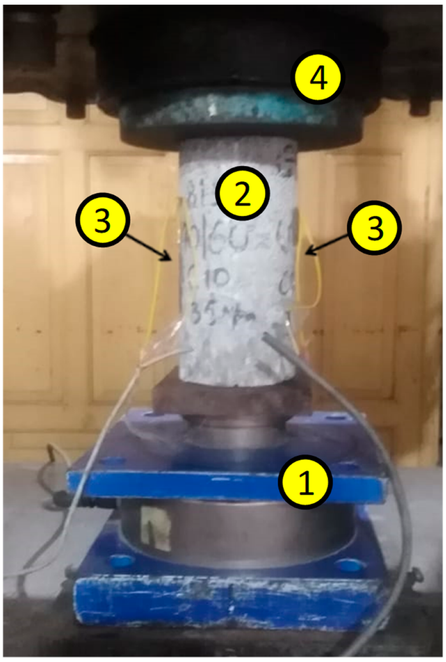
2.4.3. Modulus of Elasticity Test

Modulus of elasticity of concrete in compression ($E_c$) was determined in accordance with ASTM C469 [50]. Two strain gauges were pasted on the surface of each test specimen at 180° to measure the compressive strain as shown in Figure 8. Displacement-controlled test was performed using load cell of 500 kN capacity connected with UTM at loading rate of 0.5 mm/min. Strain gauges and load cell were connected to data acquisition system for data recording. Figure 9 shows the testing setup to conduct modulus of elasticity test in compression. To measure $E_c$, slope of the stress–strain curve was calculated by using the following relation as per ASTM C469 [50].

$$E_c = \frac{S_2 - S_1}{\in_2 - 0.000050}, \tag{2}$$

where $E_c$ is static modulus of elasticity in compression (MPa), $S_2$ is the stress (MPa) corresponding to 40% of the ultimate load, $S_1$ is the stress (MPa) corresponding to the longitudinal strain of 50 μ, and $\in_2$ is the longitudinal strain at stress, $S_2$.

**Figure 8.** Samples with strain gauges pasted on their surface.




1. Load cell 2. Test specimen
3. Strain gauges 4. Machine end platen

**Figure 9.** Setup for modulus of elasticity test in compression.

2.4.4. Ultrasonic Pulse Velocity Test

The ultrasonic pulse velocity (UPV) test was performed following ASTM C597 [51]. To determine the UPV value of each test specimen, standard UPV apparatus was used as shown in Figure 10. As per standard procedure, the time to travel by the wave between transmitter and receiver placed at the ends of the specimen is measured using standard device, and then based on length of each specimen, UPV is calculated using Equation (3).

$$V = \frac{L}{T}, \quad (3)$$

where $V$ is the pulse velocity (m/s), $L$ is the distance between the centers of transducers (m), and $T$ is transmission time (s). The calculated values of UPV were used to rate the quality of concrete sample. The criteria regarding the quality of concrete as suggested in previous studies [52,53] has been used in this study.

**Figure 10.** UPV testing device.

## 3. Results and Discussion

In this section, the results of each test performed are presented and discussed in detail. Table 5 summarizes the test results of all 28 different concrete mixes. As mentioned earlier, for each concrete composition, three samples were tested, and the average values were plotted and presented in this paper. In the table, 'A.R' stands for aspect ratio of the specimen.

### *3.1. Density of Concrete*

The density of concrete was measured after 24 h of casting to analyze the degree of compaction of various concrete compositions prepared using different techniques. The density of concrete RAC-30F70C with 10% cement content ranges from 2073 to 2201 kg/m$^3$ for applied pressure of 25 MPa to 45 MPa, while for concrete RAC-40F60C with 10% cement, the range is from 2133 to 2233 kg/m$^3$. Similarly, for 15% cement content, these values were varied from 2156 to 2278 kg/m$^3$ and 2181 to 2277 kg/m$^3$ for RAC-30F70C and RAC-40F60C, respectively. The density of RAC tends to increase with the increase in the applied pressure as shown in Figure 11a, and this is mainly attributed to the improved packing of concrete resulting in reduced porosity. Figure 11b shows a similar trend for NAC samples cast using CCT. The density of NAC cast using CCT was higher than that of RAC having similar composition. The density of concrete specimens prepared using the conventional vibration method was 2068 kg/m$^3$ and 2221 kg/m$^3$ for RAC-30F70C and RAC-40F60C, respectively, with 10% of cement. Similarly, for 15% cement contents, these values were 2230 kg/m$^3$ and 2265 kg/m$^3$ for 30F70C and 40F60C, respectively. These values are comparable to that of samples cast by CCT.

**Table 5.** Test results of density, compressive strength, elastic modulus, and ultrasonic pulse velocity.

| Sr. No. | Concrete Designation | Cement Content | Applied Pressure MPa | Density $kg/m^3$ | Compressive Strength, MPa A.R = 2 | Compressive Strength, MPa A.R = 1 | Elastic Modulus MPa | Ultrasonic Pulse Velocity Values km/s | Ultrasonic Pulse Velocity Quality |
|---|---|---|---|---|---|---|---|---|---|
| 1 | RAC-30F70C | 10% | 25 | 2073 | 6.62 | 9.0 | 9.2 | 3.337 | Questionable |
| 2 | | | 35 | 2137 | 6.7 | 11.5 | 10 | 3.573 | Questionable |
| 3 | | | 45 | 2201 | 8.7 | 12.6 | 12.05 | 3.646 | Good |
| 4 | | 15% | 25 | 2156 | 16.1 | 20.8 | 13.27 | 4.053 | Good |
| 5 | | | 35 | 2218 | 20.5 | 27.0 | 17.24 | 4.215 | Good |
| 6 | | | 45 | 2278 | 13.04 | 16.7 | 21.47 | 3.580 | Questionable |
| 7 | RAC-40F60C | 10% | 25 | 2133 | 11.3 | 13.7 | 12.54 | 3.890 | Good |
| 8 | | | 35 | 2173 | 11.76 | 16.0 | 12.78 | 4.091 | Good |
| 9 | | | 45 | 2233 | 11.86 | 19.0 | 13.25 | 4.104 | Good |
| 10 | | 15% | 25 | 2181 | 17.86 | 18.7 | 14.37 | 4.369 | Good |
| 11 | | | 35 | 2293 | 18.88 | 19.2 | 16.55 | 4.452 | Good |
| 12 | | | 45 | 2277 | 18.57 | 22.3 | 17.45 | 4.066 | Good |
| 13 | NAC-30F70C | 10% | 25 | 2318 | 11.82 | 12.8 | 16.74 | 4.443 | Good |
| 14 | | | 35 | 2328 | 13.6 | 13.5 | 18.51 | 4.463 | Good |
| 15 | | | 45 | 2390 | 12.17 | 16.7 | 22.87 | 4.602 | Excellent |
| 16 | | 15% | 25 | 2325 | 19.29 | 25.4 | 25.193 | 4.504 | Excellent |
| 17 | | | 35 | 2368 | 20.71 | 27.7 | 26.492 | 4.626 | Excellent |
| 18 | | | 45 | 2416 | 22.5 | 30.4 | 28.472 | 4.716 | Excellent |
| 19 | NAC-40F60C | 10% | 25 | 2337 | 13.05 | 14.5 | 14.861 | 3.804 | Good |
| 20 | | | 35 | 2363 | 14.69 | 16.7 | 18.07 | 3.814 | Good |
| 21 | | | 45 | 2383 | 15.26 | 20.8 | 24.037 | 3.969 | Good |
| 22 | | 15% | 25 | 2363 | 19.92 | 22.4 | 20.571 | 4.185 | Good |
| 23 | | | 35 | 2406 | 22.84 | 24.5 | 24.64 | 4.234 | Good |
| 24 | | | 45 | 2460 | 20.69 | 26.0 | 27.34 | 4.285 | Good |
| 25 | RAC-30F70C-V | 10% | Compaction by vibration | 2068 | 5.9 | 8.5 | 10.65 | 3.791 | Good |
| 26 | | 15% | | 2230 | 11.43 | 15.2 | 13.18 | 3.995 | Good |
| 27 | RAC-40F60C-V | 10% | | 2221 | 12.14 | 13.5 | 11.77 | 3.831 | Good |
| 28 | | 15% | | 2265 | 14.83 | 17.4 | 14.82 | 3.890 | Good |

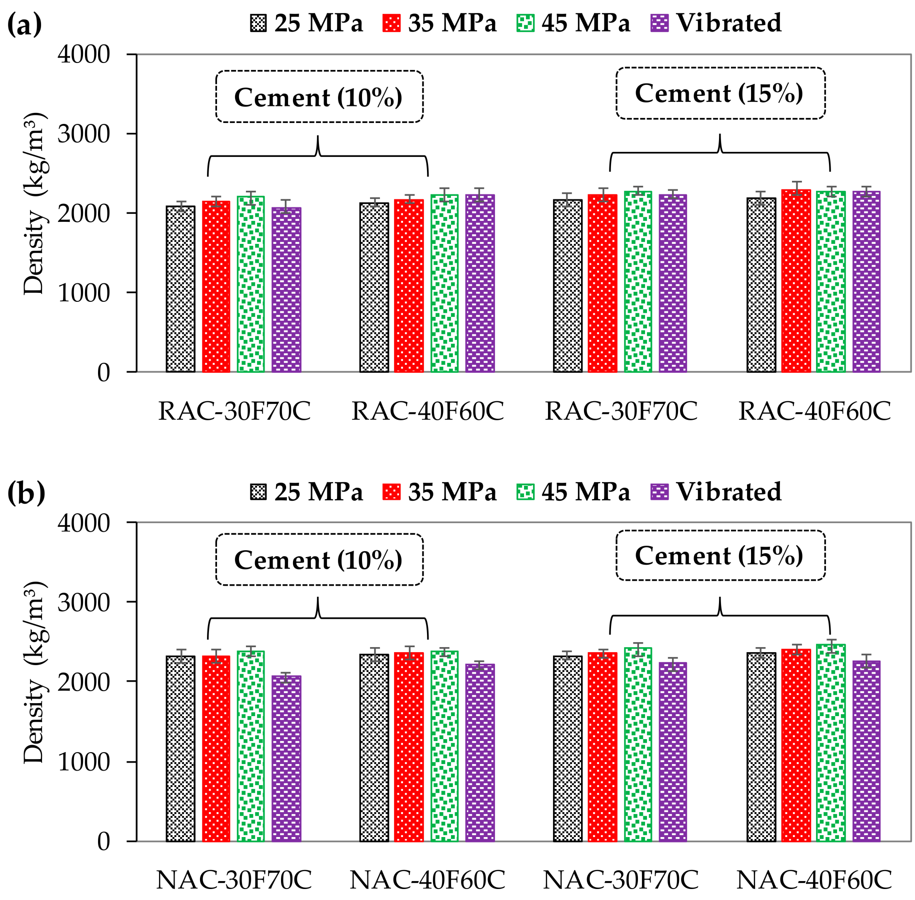



**Figure 11.** Influence of casting technique and applied pressure on density of (**a**) RAC, and (**b**) NAC.

### 3.2. Compressive Strength

The compressive strength of all concrete compositions for the aspect ratio (AR) of 1 and 2 is summarized in Table 5. Figure 12 shows the compressive strength of RAC and NAC specimens with the aspect ratio of 1 and 2 containing 10 and 15% of cement contents. It is depicted from the results presented in Figure 12a that the specimens prepared using 10% cement content could not achieve the target strength of 15 MPa. However, with the increase in the cement content to 15%, RAC-40F60C and RAC-30F70C under the applied pressure of 25 and 35 MPa, respectively, achieved the target strength. The decrease in the compressive strength at 45 MPa casting pressure was due to the expulsion of water resulting in unavailability of a sufficient amount of water required for the hydration process. For the specimen having an aspect ratio of 1, RAC-40F60C achieved the target strength for all applied pressure at the cement content of 10% as shown in Figure 12b. Results presented in Figure 12c,d for NAC specimens at various contents of cement show that most of the concretes achieved the target strength of 15 MPa except for NAC-30F70C prepared using the model with an aspect ratio of 2 and 10% of cement. Furthermore, it is also observed that concrete compositions with the use of NA exhibited higher strength compared to RA which is mainly attributed to the inferior properties of RA. With the increase in the cement content to 15% using 30:70 ratio of fine to coarse aggregates, all tested specimens achieved the target compressive strength of 15 MPa except RAC specimens prepared under the applied pressure of 45 MPa as shown in Figure 12; this is due to the fact discussed above related to the expulsion of water. The effect of the sample aspect ratio on the compressive strength is also evident in the results. The compressive strength observed for the specimens with an AR of 1 was more as compared to the one with an AR of 2. This fact is of great importance when such a concrete will be used in the manufacturing of masonry units of standard size generally having an aspect ratio less than 1.

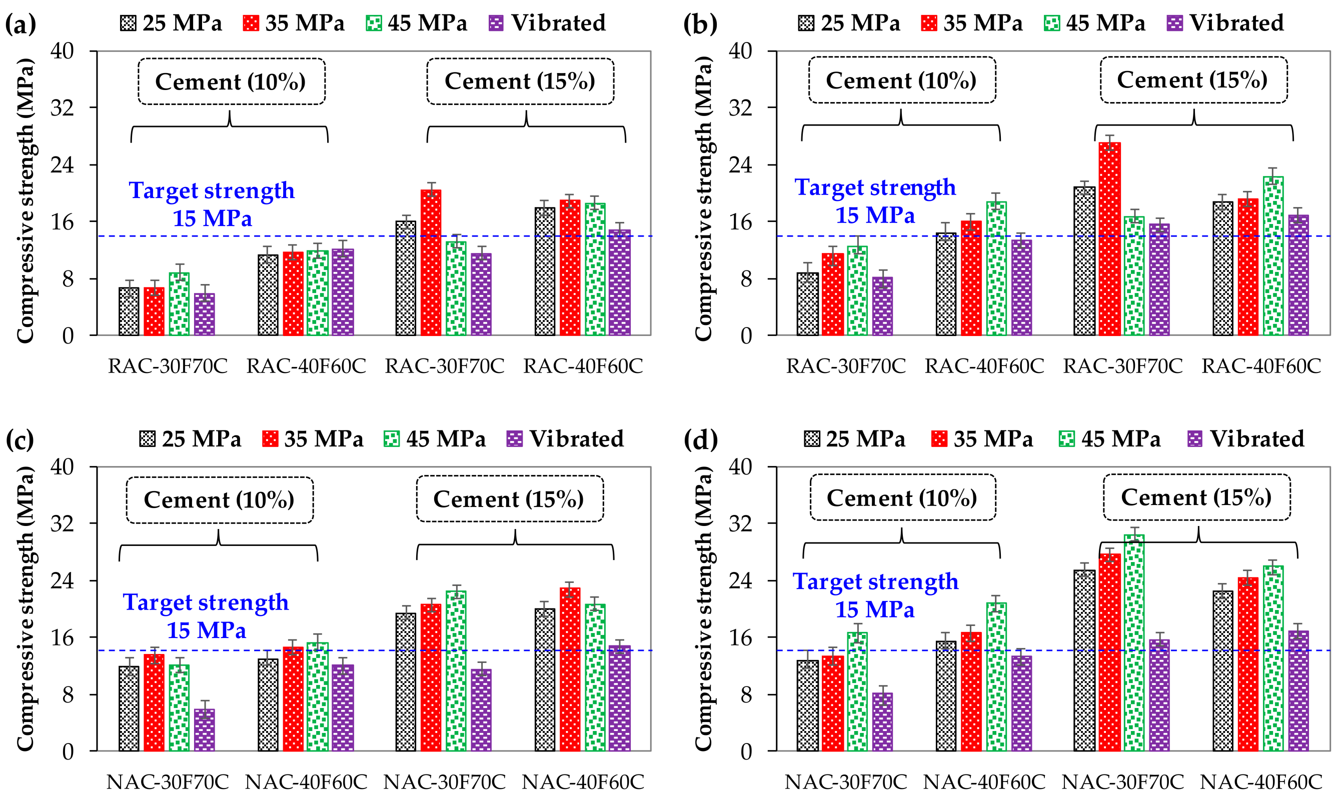



**Figure 12.** Compressive strength of concrete specimens for (**a**) RAC with aspect ratio of 2, (**b**) RAC with aspect ratio of 1, (**c**) NAC with aspect ratio of 2, and (**d**) NAC with aspect ratio of 1.

*3.3. Modulus of Elasticity in Compression ($E_c$)*

Figure 13a,b shows the modulus of elasticity of the specimens using cement contents of 10% and 15%, respectively. For RAC compositions, the highest $E_c$ value of 21.47 GPa was exhibited by composition 30F70C having 15% cement cast under the applied pressure of 45 MPa. Improvement in the E-value was observed with the increase of casting pressure from 25 MPa to 45 MPa and cement content from 10 to 15%. The modulus of elasticity of RAC specimens cast by conventional technique were also presented in the same figure. The positive effect of CCT was observed on the E-value as compared to the conventional casting technique. It may be noted that NACs showed the highest modulus of elasticity for all compositions, and observations were in line with the compressive strength results.

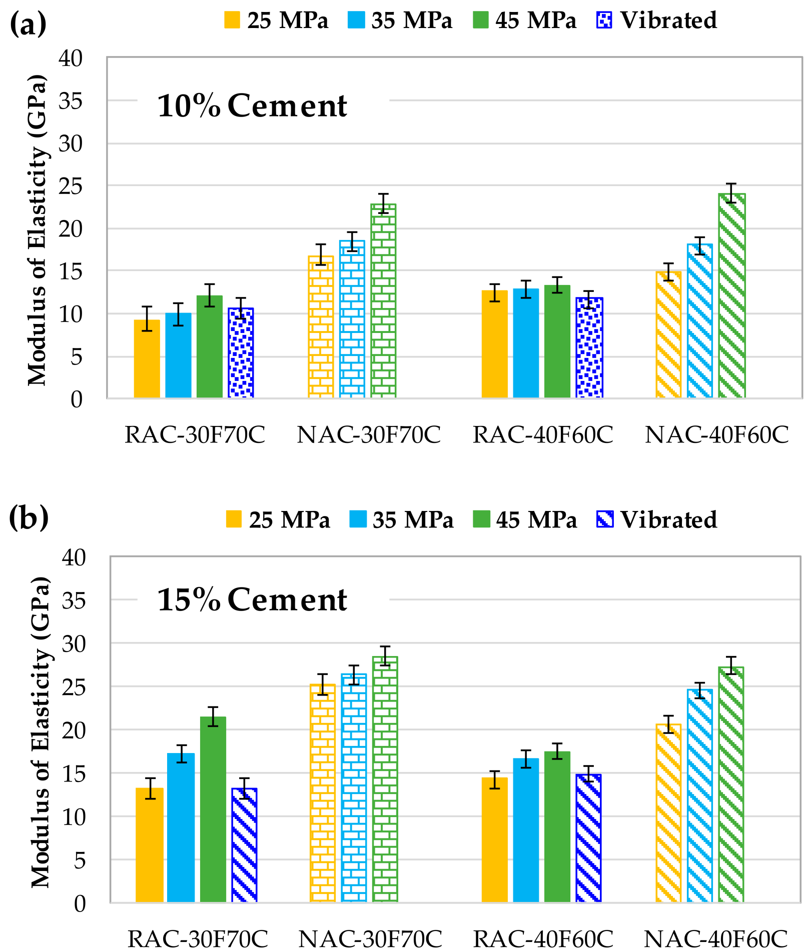



**Figure 13.** Modulus of elasticity of concrete with (**a**) 10% of cement content, and (**b**) 15% of cement content.

*3.4. Ultrasonic Pulse Velocity (UPV)*

UPV values of RAC and NAC specimens prepared by CCT are presented in Table 5. The higher value of UPV shows that lesser time is required for the signal to travel which indicates poor quality of concrete and vice versa. The criteria regarding the quality of concrete based on UPV values as suggested by [52,53] has been used in this study. Accordingly, the quality of various RAC and NAC mixes is also highlighted in Table 5. It is important to mention here that the proposed criteria to assess the quality of concrete was based on the conventional casting technique. The same approach has been used to check the quality of concrete prepared through CCT. The quality of most of the RAC mixes was ranked as good with a few exceptions, while the quality of NAC mixes was found to be excellent or good as described in Table 5. For RAC mixes for which the quality indicator was poor, lower compressive strength was also reported for these compositions.

*3.5. Observations*

Based on the results presented in Section 3, the following observations were made.

- Concrete specimens prepared using CCT showed improvement in the various properties, such as compressive strength, modulus of elasticity, and quality assessment through UPV with the increase in the casting pressure. Accordingly, to prepare RAC mix using CCT, a higher casting pressure is recommended to obtain the improvement in the mechanical performance.
- RA and NA were used to prepare the concrete using 30:70 and 40:60 ratios of fine to coarse aggregates, respectively. The density and other mechanical properties of NAC were higher than RAC. Old mortar attached to RA increases the porosity which results in reducing the density and mechanical performance of RAC. Figure 14a,b show the influence of proportion of RFA and RCA on the compressive strength and modulus of elasticity of RAC, respectively. The compressive strength and E-value exhibited by the RAC using 40:60 ratio of RFA to RCA was higher than the other mix ratio (i.e., 30:70). Therefore, it is suggested to use 40% of RFA and 60% of RCA to prepare the RAC with the use of 100% RAs.

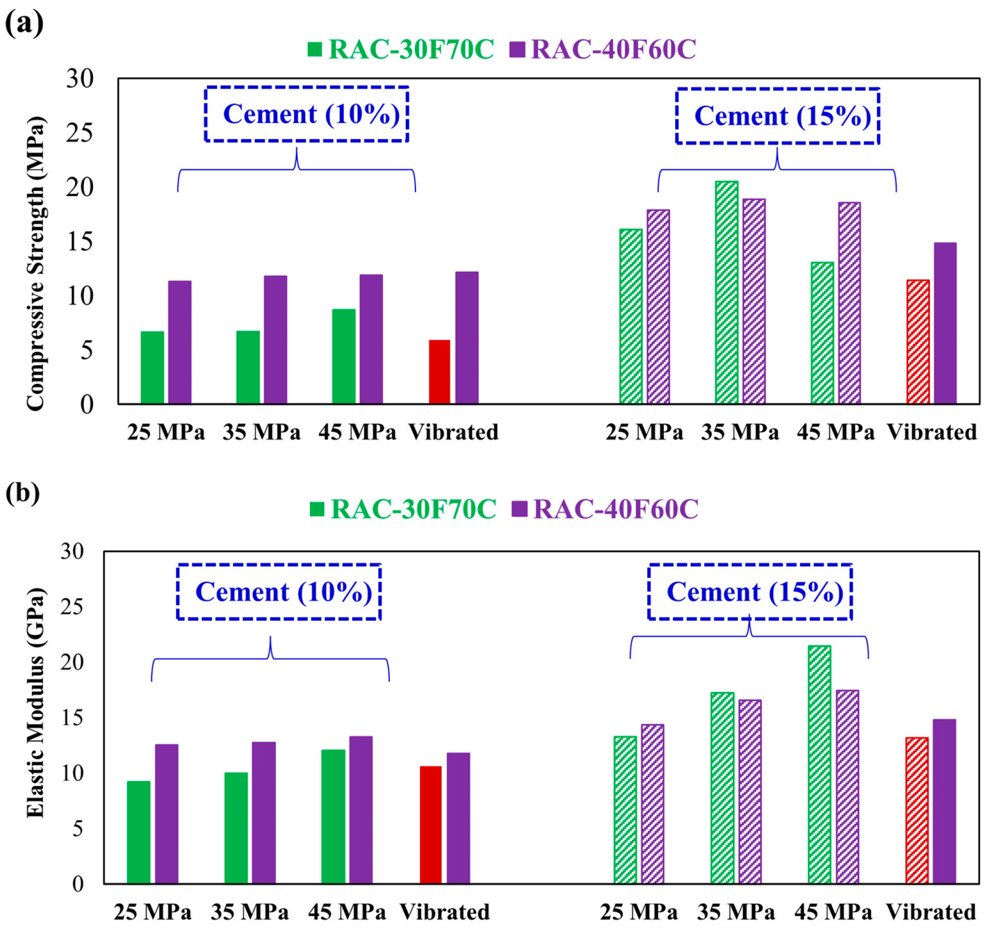



**Figure 14.** Influence of recycled aggregates (RCA and RFA) on (**a**) compressive strength, and (**b**) elastic modulus.

- Two different dosages of cement were used to prepare the concrete compositions. For RAC, the compressive strength as well as the modulus of elasticity of concrete tend to increase with the increase in cement contents as is evident from Figure 14a,b. A slight improvement in the density of concrete was also observed with increasing cement content.

## 4. Analytical Modeling

In the past studies, based on experimental studies, analytical models were developed to predict compressive strength and elastic modulus of RAC prepared by partial replacement of NA with RA. However, no analytical model is available to estimate the mechanical properties of RAC with 100% replacement of NA with RFA and RCA. Moreover, the existing analytical models for RAC and NAC were based on the experimental data obtained from the specimens prepared using the conventional casting technique. In this section of the paper, the existing analytical models have been analyzed using the experimental data presented in this study, and novel analytical models have been proposed by considering the effect of 100% replacement of NA with RFA and RCA and the compression casting technique.

### *4.1. Analytical Model for Compressive Strength Based on Density of Concrete*

From the existing literature, most relevant models for the prediction of compressive strength based on density of concrete were selected for RAC and NAC. The details of selected models are presented in Table 6. Based on the results of density and compressive strength presented in Table 5 of this study, the selected models were evaluated. The accuracy of models was assessed based on two statistical parameters, average absolute error (AAE) and mean (M) calculated using Equations (4) and (5), respectively. The AAE indicates the overall accuracy of the model and can have a value from zero to infinity, with value zero showing that the model is perfect. The second parameter, mean (M), represents the average overestimation or underestimation. If the value of M is less than one, it means the model underestimates the results, and if it is more than one, it means the model overestimates the results.

$$AAE = \frac{\sum_{i=1}^{N} |(exp_i - ana_i)/exp_i|}{N}, \tag{4}$$

$$M = \frac{\sum_{i=1}^{N} (ana_i/exp_i)}{N}, \tag{5}$$

**Table 6.** Analytical models for prediction of compressive strength based on density.

| Sr. No. | Reference | Analytical Model | Casting Technique and Aggregate Type |
|---|---|---|---|
| 1 | Xiao et al. [54] | $f'_c = 0.069\rho - 116.1$ | Conventional casting using recycled aggregates |
| 2 | Lim et al. [55] | $f'_c = 21\left(\frac{w}{c}\right)^{-1}\left(\frac{\rho}{2400}\right)^{1.6}$ | Conventional casting using natural aggregates |

As shown in Figure 15, the analytical models of Xiao et al. [54] and Lim et al. [55] highly overestimated the results with AAE more than 100%. This difference is due to the different nature of concrete for which these models were developed as compared to the one analyzed in this study. For this reason, new models were proposed for RAC and NAC separately based on the regression analysis of results presented in Table 5. The proposed models are presented as Equations (6) and (7) to predict the compressive strength based on the density of RAC and NAC, respectively.

$$f'_c = 0.064\rho - 123.4, \tag{6}$$

$$f'_c = 0.089\rho - 193.0, \tag{7}$$

where $f'_c$ is the compressive strength in MPa, and $\rho$ is the mass density in kg/m$^3$. The proposed Equations (6) and (7) were evaluated against the experimental data presented in this study as shown in Figure 15a,b. The proposed equations predicted the results with acceptable accuracy, with AAE less than or close to 15%.

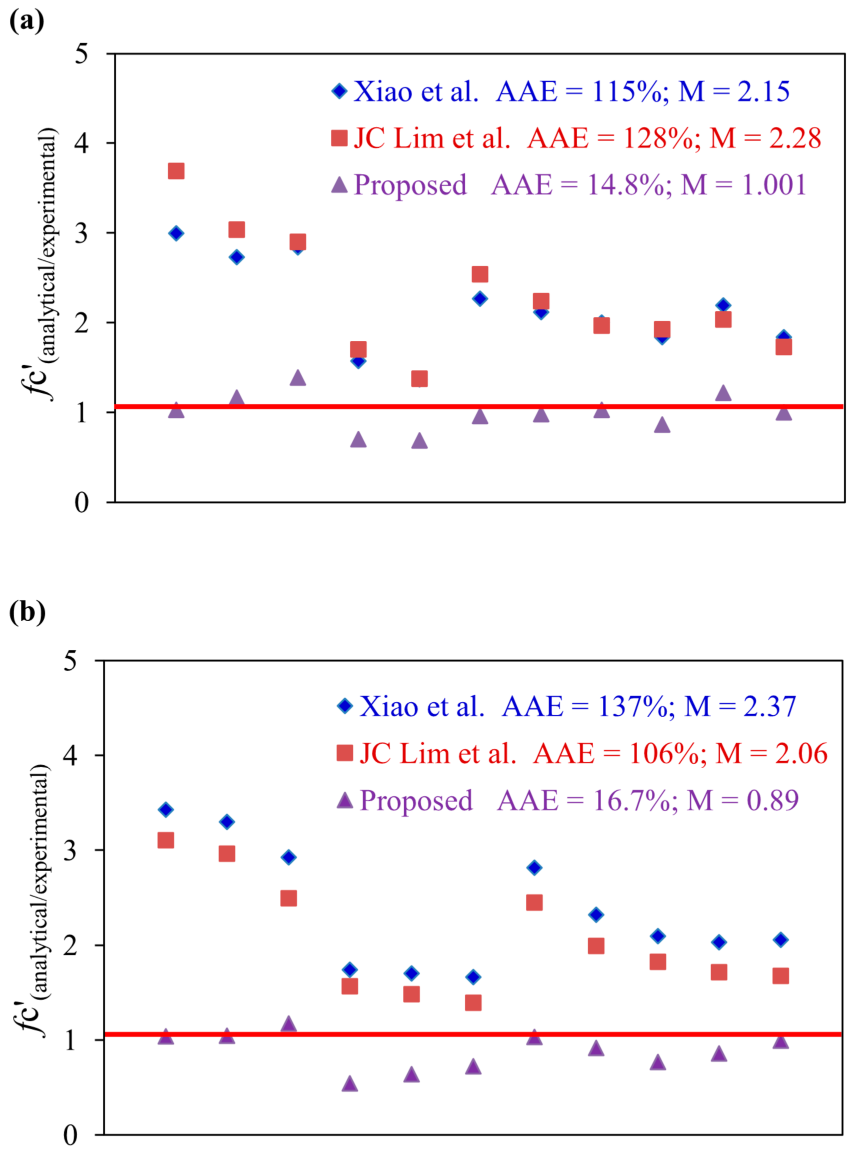



**Figure 15.** Analysis of existing and proposed analytical models for compressive strength of (**a**) RAC prepared through CCT, and (**b**) NAC prepared through CCT [54,55].

*4.2. Analytical Model for Elastic Modulus Based on Compressive Strength and Density of Concrete*

The existing models developed to predict the modulus of elasticity of RAC and NAC based on the compressive strength and density were summarized in Table 7. These models were used to calculate the E values based on the experimental data provided in Table 5 and were evaluated based on statistical parameters "AAE and M". Experimental and analytical results based on the existing models for NAC and RAC were presented in Figure 16a,b, respectively. It can be observed from the results that existing models could not predict the modulus of elasticity of compressed concrete prepared using RFA and RCA. However, two models developed by Lim et al. [55] and Antonio et al. [56] for NAC predicted the elastic modulus with acceptable accuracy (AAE of 12.7% and 9.7%, respectively). By using the approach of Lim et al. [55], analytical models for compressed RAC and NAC have been proposed using linear regression analysis of the results of this study and presented in Equations (8) and (9), respectively.

$$E = 4300\sqrt{f_c'}\left(\frac{\rho}{2400}\right)^{2.88}, \quad (8)$$

$$E = 5100\sqrt{f_c'}\left(\frac{\rho}{2400}\right)^{2.027}, \quad (9)$$

where $E$ is the elastic modulus of concrete in MPa, $f_c'$ is the compressive strength in MPa, and $\rho$ is the mass density in $kg/m^3$. The proposed models were used to predict the E value of concrete and the results were plotted as shown in Figure 16a,b, respectively. The proposed equations predicted the results with reasonable accuracy of AAE less than 5%.

**Table 7.** Existing analytical models for prediction of elastic modulus.

| Sr. No. | Reference | Prediction Equation | Casting Technique and Aggregate Type |
|---|---|---|---|
| 1 | Kakizaki et al. [57] | $E = 1.9 \times 10^5 \times \left(\frac{\rho}{2300}\right)^{1.5} \times \sqrt{\frac{f_c'}{2000}}$ | Conventional casting and RA |
| 2 | Antonio et al. [56] | $E = 2.85 \times f_c'^{0.63}$ | Conventional casting and RA |
| 3 | Ravindrarajahet al. [58] | $E = 7.77 \times f_c'^{0.33}$ | Conventional casting and RA |
| 4 | Antonio et al. [56] | $E = 4.55 \times f_c'^{0.5}$ | Conventional casting and NA |
| 5 | Lim et al. [55] | $E = 4400 \times \sqrt{f_c'} \times \left(\frac{\rho}{2400}\right)^{1.4}$ | Conventional casting and NA |
| 6 | ACI 318-02 [59] | $E = 0.0427 \times \sqrt{f_c'} \times (\rho)^{1.5}$ | Conventional casting and NA |

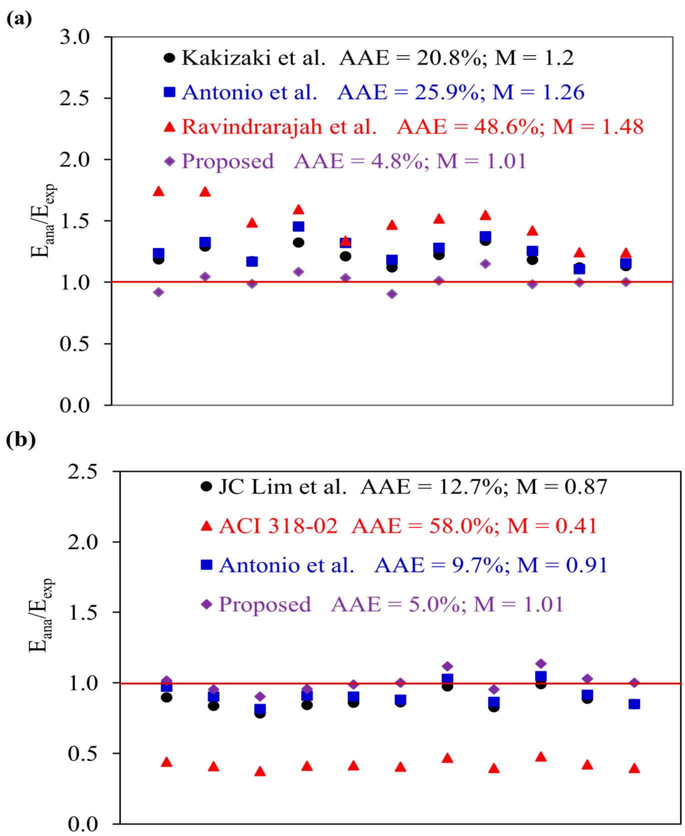



**Figure 16.** Evaluation of existing and proposed analytical models for elastic modulus of (**a**) RAC and (**b**) NAC [55–59].

## *4.3. Relationship between Compressive Strength and Ultrasonic Pulse Velocity*

The ultrasonic pulse velocity test is used to assess the quality of the concrete. Researchers in the past have developed relationships between ultrasonic pulse velocity and compressive strength of the concrete. From the existing literature, most relevant models for the prediction of compressive strength of NAC based on UPV value were selected as summarized in Table 8. The analytical results obtained by employing proposed equations and experimental results have been presented in Figure 17a,b for RAC and NAC, respectively, prepared by CCT. The AAE for the results obtained through the selected models for RAC was more than 15%, indicating the inability of models to predict the compressive strength of RAC prepared by CCT having 100% RAs. Similarly, for NAC, the minimum AAE was 12.6% for the Kurtulus and Bozkurt [60] model. Due to the inability of existing analytical models for the precise prediction of the results for RAC and NAC prepared through CCT, models have been proposed based on the linear relation between UPV and $f_c'$ as suggested by Qasrawi et al. [61]. The following expressions can be used to predict the compressive strength of RAC and NAC based on the UPV test data, respectively.

$$f_c' = 9.05(UPV) - 20.86, \quad (10)$$

$$f_c' = 12.98(UPV) - 31.96, \quad (11)$$

where $f_c'$ is the compressive strength in MPa, and UPV is the ultrasonic pulse velocity in km/s. Compressive strength of RAC and NAC was calculated using the proposed analytical models and the comparison between experimental and analytical results were presented in Figure 17a,b. The proposed equations predicted the results with reasonable accuracy of AAE 10.6%, and 4.4% for Equations (10) and (11), respectively.

**Table 8.** Existing prediction models for compressive strength of concrete using UPV.

| Sr. No. | Reference | Prediction Equation | Casting Technique and Aggregate Type |
|---|---|---|---|
| 1 | Turgut [62] | $f_c' = 0.316e^{1.03UPV}$ | Conventional casting and NA |
| 2 | Kurtulus and Bozkurt [60] | $f_c' = 0.062(UPV) - 46.497$ | Conventional casting and NA |
| 3 | Qasrawi et al. [61] | $f_c' = 36.72(UPV) - 129.077$ | Conventional casting and NA |

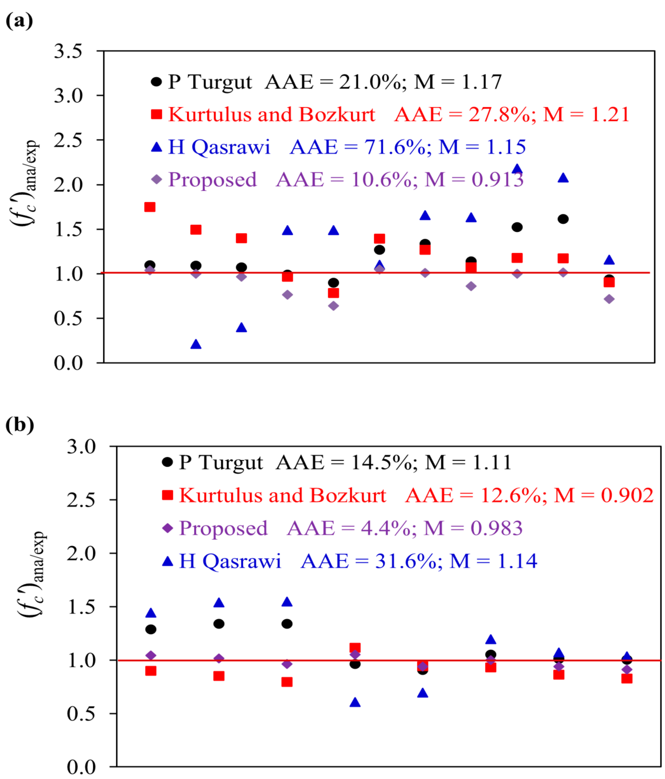



**Figure 17.** Evaluation of existing and proposed analytical models between compressive strength and UPV for (**a**) RAC prepared through CCT, and (**b**) NAC prepared through CCT [60–62].

*4.4. Relationship between Elastic Modulus and Ultrasonic Pulse Velocity*

From the existing literature, an analytical model as presented in Equation (12) developed by Kim et al. [63] for NAC was used to predict the elastic modulus of concrete from the UPV values and evaluated based on the results presented in Table 5. The comparison of experimental and analytical results is shown in Figure 18a,b for RAC and NAC prepared using CCT, respectively, where it is clear that the existing model is not able to predict the results for compressed RAC accurately. The AAE values for RAC and NAC were 66% and 17.5%, respectively, indicating the inability of the model to predict the elastic modulus. Similar analytical models to predict elastic modulus of compressed RAC and NAC have been proposed using linear regression analysis and are presented in Equations (13) and (14), respectively, where $E$ is the elastic modulus in GPa and UPV is the ultrasonic pulse velocity in km/s.

$$E = 1.7617 \times e^{0.6333 \times UPV}, \quad (12)$$

$$E = 1.668 \times e^{0.5117 \times UPV}, \quad (13)$$

$$E = 2.999 \times e^{0.4725 \times UPV}, \quad (14)$$

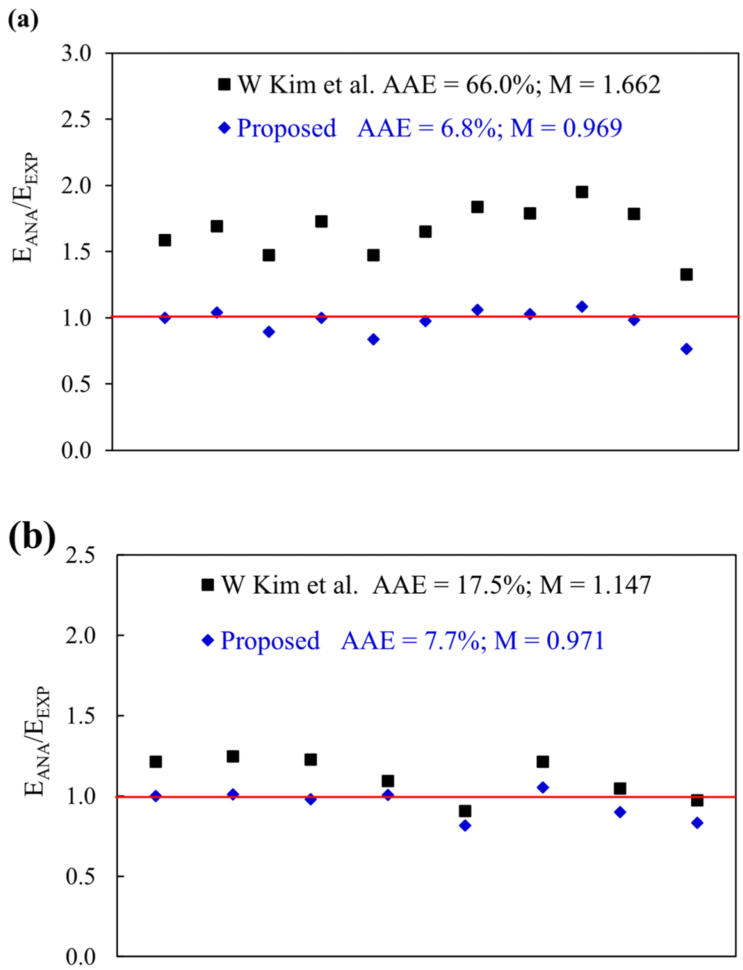



**Figure 18.** Evaluation of existing and proposed relations between elastic modulus and UPV for (**a**) RAC prepared through CCT, and (**b**) NAC prepared through CCT [63].

The results obtained through the proposed analytical models were compared with the experimental ones and presented in Figure 18a,b for RAC and NAC, respectively. The proposed equations predicted the results with reasonable accuracy of AAE 6.8% and 7.7% for RAC and NAC, respectively.

The above-presented experimental results have highlighted the positive impact of CCT on the mechanical performance of RAC which is in line with the findings of other studies available in the literature on different concrete regarding compression casting. For instance, Kazmi et al. [40] worked to develop green and eco-friendly concrete products using waste tire rubber and recycled aggregates and by employing compression casting. The study found that the RAC prepared by compression casting and containing 10–20% crumb rubber in replacement of coarse aggregates exhibited compressive strength and elastic modulus quite similar to traditional concrete without crumb rubber. Wang et al. [41] developed layered compression casting and showed that compared to traditional concrete, the modulus of elasticity and the compressive strength of concrete prepared by layered compression casting are improved up to almost 50% and 100%, respectively. Based on the findings of the research study presented in this paper and similar works reported in the literature, the use of compressing casting by the precast concrete industry for the manufacturing of concrete products of fully RAC having desired mechanical performance would promote the maximum recycling of C&D waste. This will help to achieve sustainability in the construction sector by conserving natural resources of concrete aggregates, avoiding environmental pollution caused by C&D waste, and reducing space wastage in landfills. In this research work, the RA were produced from the waste concrete of compressive strength range 21–28 MPa; investigation of the impact of parent concrete strength [64] of RA along with compression casting on the performance of fully RAC could be an interesting research topic for future studies.

## 5. Conclusions

In this contribution, a comprehensive experimental study has been conducted to observe the effect of the compression casting technique (CCT) on the physical and mechanical properties of RAC prepared using 100% recycled aggregates (both fine and coarse). The effect of applied pressure, ratio of RCA and RFA, casting technique and cement contents on the mechanical properties of RAC was assessed and compared with NAC. Moreover, analytical models based on the experimental data have been proposed to predict the mechanical properties of RAC prepared by CCT. The findings of this study made it possible to draw the following conclusions:

- The compression casting technique showed a positive impact on the mechanical properties of RAC. On average, considering all compositions tested in this study, compressive strength and elastic modulus of RAC were increased by 20–80% and 15–50%, respectively, by changing the casting method from vibration to compression casting.
- A total of 100% RAC prepared by CCT at a casting pressure of 35 MPa and cement content of 15% was able to achieve compressive strength greater than 100% NAC prepared by the conventional method of casting [i.e., through vibration].
- For CCT, the value of casting pressure is of great importance with respect to density of resulting concrete. However, the decision regarding the value of casting pressure to be used must depend upon the target strength of the resulting RAC.
- For the manufacturing of masonry units of an aspect ratio equal or less than one, CCT made it possible to design a concrete of target compressive strength of 15 MPa containing significantly less quantity of cement (i.e., 10%) and 100% RAC (40% fine + 60% coarse).
- The ultrasonic pulse velocity value exhibited by 100% RAC was increased by changing the casting technique. Further, with the increase of casting pressure in CCT, UPV value was increased, indicating improvement in quality of concrete.
- The mechanical properties of RAC and NAC compositions prepared by two ratios of fine and coarse aggregates [i.e., 30:70 and 40:60] and two cement contents [10% and 15%] in this study clearly indicated that the effect CCT depends upon is the mix ratio of coarse and fine aggregates as well as cement dosage.
- Analytical models to predict different properties of RAC and NAC prepared by CCT were developed based on the regression analysis of the results obtained in this study. The proposed models were evaluated based on statistical parameters average absolute

error (AAE) and the mean (M). The proposed analytical models were found to be able to predict the compressive strength and elastic modulus of RAC with reasonable accuracy as compared to the analytical models already existing in literature.

- In this study, the feasibility of using RAC incorporating 100% RA prepared by CCT for the manufacturing of masonry units is highlighted. However, only the effect of casting pressure is investigated. In order to be in line with field practice for the manufacturing concrete masonry unit, further investigation is recommended to be carried out to improve the effect of CCT by developing a setup to impart vibration to mold and compaction through compression at the same time.

**Author Contributions:** Conceptualization, R.H. and M.T.; methodology, R.H.; validation, R.H., M.T., and Z.-u.-N.; formal analysis, S.S., S.M.S.K. and M.J.M.; investigation, R.H. and Z.-u.-N.; resources, S.M.S.K. and M.J.M.; data curation, R.H. and S.S.; writing—original draft preparation, Z.-u.-N., S.S., S.M.S.K. and M.J.M.; writing—review and editing, R.H., S.M.S.K., and M.J.M.; visualization, S.M.S.K. and M.T.; supervision, R.H.; project administration, R.H. and M.T.; funding acquisition, R.H. and Z.-u.-N. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Higher Education Commission (HEC) Pakistan, under HEC-NRPU research grant number 9764.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Conflicts of Interest:** The authors declare no conflict of interest.

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