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Article

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Abstract

This study investigates the effect of recycled concrete aggregate (RCA) on the mechanical properties of concrete, with particular emphasis on the modulus of elasticity (Ec), at replacement levels of R25, R50, R75, and R100, compared with a reference concrete mixture containing natural aggregate (R0).

An experimental and analytical investigation was conducted using cylindrical specimens measuring 150 × 300 mm, in which the modulus of elasticity, Poisson's ratio, splitting tensile strength, and compressive strength were evaluated at different curing ages. The tests were complemented by a nonlinear finite element model of the cylinders in ABAQUS (concrete damaged plasticity) and by a statistical analysis of the compressive strength results (one-way ANOVA with Tukey's HSD post hoc test).

The experimental results demonstrated that the use of recycled concrete aggregate (RCA) resulted in a progressive reduction in the cylindrical compressive strength of concrete as the replacement level increased. At the ages of 7, 28, and 120 days, the reductions in compressive strength for the R25, R50, R75, and R100 mixtures ranged from 6.96–20.50%, 6.51–17.11%, and 3.80–18.40%, respectively, compared with the reference concrete containing natural aggregate (R0). ANOVA showed that the replacement level had a significant effect on compressive strength at 7 and 28 days ($p < 0.001$); the 25% replacement did not differ significantly from the reference concrete, significant reductions appeared from 50% replacement, and R75 and R100 were not significantly different from each other.

Increasing the proportion of RCA at the investigated replacement levels resulted in a 10–27% reduction in the modulus of elasticity of concrete (Ec), a 5–7% increase in Poisson's ratio, and a 15–26% reduction in splitting tensile strength, compared with the reference concrete (R0). The numerical model reproduced the increase in axial strain with increasing replacement, and its splitting tensile strengths were 5–16% higher than the experimental values.

An empirical equation based on the ACI 318 relationship, with reduction factors for the compressive strength ratio and the unit weight, was proposed to estimate the modulus of elasticity (Ec) of concrete containing RCA. It reproduced the measured moduli with differences between −3.6% and +2.5%, and for 9 of the 11 data points from previous studies the predictions were within ±15% of the reported values.

Keywords: natural aggregate, recycled aggregate, splitting tensile strength, modulus of elasticity, Poisson's ratio, finite element analysis, ANOVA.

Introduction

Concrete is one of the most important construction materials because of its positive characteristics, particularly its low cost and local availability. In recent years, the demolition and reconstruction of buildings have increased to accommodate new purposes, because buildings have reached the end of their design service life, or as a result of wars affecting some countries. This has led to the accumulation of large quantities of waste, a significant portion of which consists of concrete, creating a new challenge for the environment and society. Global concrete consumption is estimated at approximately 55 billion tons.[1] However, the increasing demand for the use and production of concrete is accompanied by a shortage of good-quality raw materials available locally. Furthermore, the destruction caused by armed conflicts and wars in countries such as Syria and Yemen has generated unprecedented quantities of construction and demolition waste (CDW), posing an increasing environmental challenge due to the difficulties associated with its management and safe disposal. In this context, the recycling of old concrete and the use of the resulting recycled aggregate in the production of new concrete mixtures has emerged as a promising approach to reducing waste accumulation and improving the efficient utilization of natural resources.[2]

Recent studies on the elastic modulus of recycled aggregate concrete (RAC) have moved toward mechanism-based and data-driven models. At the mesoscale, Zhang et al.[3] proposed a Monte Carlo numerical method that accounts for the real shape and nonuniform distribution of the coarse aggregate, and found that the elastic moduli of the cement paste and of the coarse aggregate, and the

coarse aggregate content, were the most influential parameters. Liang et al.[4] combined experiments on modelled recycled aggregate concrete with finite element simulation in ABAQUS and reported that the elastic modulus of the old mortar had the greatest effect on the stiffness of the concrete, while changes in the width and modulus of the interfacial transition zone changed the response by less than 8.9%. Data-driven models have also been developed: Zheng et al.[5] trained hybrid neural networks on 400 data rows collected from the literature, and Lu et al.[6] compiled 1161 RAC samples and reached R^2 = 0.912 and an RMSE of 1.65 GPa with a TabPFN model, identifying compressive strength as the most influential input. Lu et al.[6] also noted that no universal analytical relationship exists for the elastic modulus of RAC, that code equations derived for natural aggregate concrete overestimate it, and that correction factors for replacement ratio or density have improved local accuracy without generalizing across datasets. At the structural level, RAC has also been studied in shear[7] and torsion,[8] where the stiffness of the material governs deformations. These findings motivate a simple relationship based on a well-known code equation, calibrated with the measured compressive strength and unit weight, as proposed in this study, while recognizing that its validity is limited to the range of the data. So As a result of the severe wartime conditions in Syria and some other countries, a large number of buildings were demolished, leaving substantial quantities of concrete waste. One approach to addressing this situation is to recycle these wastes and reuse them.[2]

The main objective of this research is to make optimal use of these wastes by incorporating them into structural elements as partial or total replacement of natural aggregate at replacement ratios of R0, R25, R50, R75, and R100, and to investigate the mechanical properties of concrete containing recycled aggregate, including compressive strength, modulus of elasticity, Poisson's ratio, and splitting tensile strength.

Literature Review

Park[9] investigated the effect of the age of recycled aggregate. Two types of recycled aggregate were considered: the first was obtained from newly cast concrete crushed at the age of 28 days, and the second was obtained from old concrete waste. These two types were used to produce concrete mixtures, and selected mechanical properties were compared with those of conventional concrete produced using natural aggregate. Two cement contents, 250 kg/m³ and 350 kg/m³, were used in each mixture to investigate the effect of increased cement content on mechanical properties. The results

showed that concrete containing recycled aggregate was weaker than concrete containing natural aggregate regardless of the aggregate source. However, concrete produced using recycled aggregate obtained from old concrete performed better than that produced using recycled aggregate from newly cast concrete: the compressive strength reduction was 16% for the old-concrete aggregate and 25% for the newly cast concrete aggregate compared with natural aggregate concrete. The study also showed that increasing the cement content improved mechanical properties, including compressive strength and modulus of elasticity.

Al-Akkari and Al-Amoudi[10]prepared concrete mixtures with recycled aggregate replacement ratios of 0%, 25%, 50%, 75%, and 100%. She concluded that the average cylindrical compressive strength decreased as the recycled aggregate replacement ratio increased, with reductions of 7.48%, 11.1%, 15.84%, and 18.88%, respectively, compared with the reference specimens made with natural aggregate.

Konin and Kouaido[11] conducted a study on concrete mixtures made with natural aggregate and 100% recycled aggregate obtained from concrete demolition debris. They investigated the effect of cement content on compressive strength using five different cement contents (250, 300, 350, 400, and 450 kg/m³), while adjusting the water content to obtain an Abrams cone slump of 8 cm. The results showed that the difference in strength between natural-aggregate and recycled-aggregate concrete was smaller when cement contents of 250–300 kg/m³ were used. When a cement content higher than 300 kg/m³ was used, the change in compressive strength was 8%; however, the quality obtained with cement contents below 300 kg/m³ was poor. Increasing the cement content above this level improved the properties and resulted in better performance.

Gonzalez and Martinez[12] conducted a study to investigate the structural properties of concrete produced with recycled aggregate. The study focused on two aspects. First, the properties of recycled aggregate available on the market in Spain were investigated. Despite the noticeable differences in density and water absorption between natural and recycled aggregate, the latter was found to be

suitable for producing new concrete. Second, the basic properties of concrete were investigated. Several mixtures were designed using natural aggregate according to Spanish specifications, with w/c = 0.55 and a cement content of at least 300 kg/m³. To obtain a strength of at least 30 MPa, a recycled aggregate replacement ratio of 50% was required. Based on the physical and mechanical properties, including compressive strength, splitting tensile strength, and modulus of elasticity, the performance of mixtures containing natural and recycled aggregate was considered acceptable.

Materials and Method

Cement:

Ordinary Portland cement of strength class 32.5 MPa was used, with a cement content of 400 kg/m³.

Superplasticizer:

The superplasticizer used in this study was Hyperplast ES901, a high-performance water-reducing admixture conforming to ASTM C494, Type G,[13] based on polycarboxylic polymers. To determine the appropriate dosage, several dosages were tested within the manufacturer's recommended range of 0.5–2.2%. Workability was evaluated for a number of trial mixtures. Accordingly, dosages of 0.5%, 0.5%, 1%, and 1.5% by mass of cement were adopted for the replacement ratios R25, R50, R75, and R100, respectively, and were added to the mixing water during preparation of the mixtures.

Natural Aggregate and Recycled Aggregate:

The natural aggregate used consisted of four types: coarse gravel, fine gravel, crushed sand, and fine sand. Sourcing standardized recycled aggregate presented a major challenge due to the lack of specialized commercial recycling facilities in Syria. To overcome this, demolition waste was gathered locally from Homs, processed through a private crushing plant, and subsequently screened at the Building Materials Laboratory of Homs University

in the industrial area of Homs, manually sorted, crushed, and subsequently screened in the Building Materials Laboratory of the Faculty of Civil Engineering, Homs University, as shown in Figure (1). [Insert Figure 1 here].

Several tests were conducted on the natural and recycled aggregate, including specific gravity, Los Angeles abrasion loss, and sand equivalent tests, in the Roads and Soil Laboratories of the Faculty of Civil Engineering, Homs University, as shown in Figure (2). [Insert figure 2 here].

After screening the recycled aggregate in the laboratory, three aggregate size fractions were obtained: coarse gravel with a sieve size of 16–25 mm, fine gravel with a sieve size of 4.75–16 mm, and crushed sand with a sieve size of 1.18–4.75 mm.

Table (1) presents the physical and mechanical properties of the natural and recycled aggregates, including specific gravity, Los Angeles abrasion loss, and sand equivalent, obtained from the preceding tests in accordance with the adopted specifications AASHTO T 69, ASTM C127,[14] and ASTM C77. [Insert Table 1 here].

To obtain a particle size distribution that complies with the requirements of ASTM C33,[15] sieve analysis was conducted on both the natural aggregate and recycled concrete aggregate at the Building Materials Laboratory, Faculty of Civil Engineering, University of Homs, Syria. The final proportions of the natural aggregate constituents were 37% coarse gravel, 27% fine gravel, 23% crushed sand, and 13% fine sand. For the recycled concrete aggregate, the constituent proportions were 28% coarse gravel, 34% fine gravel, 21% crushed sand, and 17% fine sand. The different aggregate fractions were blended according to these proportions, ensuring that the overall particle size distribution remained within the upper and lower limits specified by the standard, as shown in Figure 3.

[Insert figure 3 here].

Table (2) presents the masses of materials used in the study per cubic meter for mixtures containing natural and recycled aggregate. [Insert Table 2 here].

Comparison between Natural Aggregate and Recycled Aggregate:

Specific Gravity: The specific gravity of recycled aggregate is lower than that of natural aggregate, which is consistent with the findings of previous studies.[16,17]

Abrasion Loss: The Los Angeles abrasion loss was 20.13% for natural aggregate and 31.53% for recycled aggregate. The higher loss observed for recycled aggregate is attributed to the old adhered mortar, which disintegrates more readily.[15,18] According to the Ministry of Housing and Utilities,[19] the maximum permissible Los Angeles abrasion loss is 40%; therefore, this aggregate is suitable for producing concrete mixtures.

Absorption: The absorption of recycled aggregate was 5.11%, which is higher than the 2.16% absorption of natural aggregate. This is attributed to the old mortar adhered to the surface of recycled aggregate, which contains a relatively high proportion of pores. This observation is consistent with previous studies.[20,21]

Specimen Tests:

Several tests were conducted in this study on the mixtures and concrete specimens to determine selected properties. A brief description of some of these tests is provided below.

Abrams Cone Slump:

The slump test was conducted using an Abrams cone in accordance with ASTM C143-74.[22] Figure (4) presents the Abrams slump values for the different replacement ratios. The slump decreased as the recycled aggregate replacement ratio increased: the slump was 7 cm for the mixture containing R100 recycled aggregate and 11 cm for the mixture containing natural aggregate. This is attributed to the highly porous old mortar adhered to the surface of recycled aggregate, which causes it to absorb water more rapidly than natural aggregate. This has also been confirmed by previous studies.

[Insert figure 4 here].

Compressive Strength: (ASTM C39-72)[23] was adopted to determine the compressive strength. Figure (5) shows the testing machine, the compression test, and the failure mode of the specimens. The dimensions and masses of the specimens were recorded. Three cylindrical specimens from each replacement ratio were tested at 7 days, three cylindrical specimens from each replacement ratio were

[Insert figure 5 here].

[Insert Table 3 here].

[Insert Table 4 here].

It can be observed that the cylindrical compressive strength decreased as the recycled aggregate replacement ratio increased. At 7 days, the reductions were 6.96%, 8.85%, 18.81%, and 20.5%; at 28 days, they were 6.5%, 9.9%, 15.7%, and 17.1%; and at 120 days, they were 3.8%, 7.6%, 13.3%, and 18.4% for replacement ratios of R25, R50, R75, and R100, respectively, compared with the reference specimens with R0 replacement. The unit weight decreased by approximately 0.9%–2.6% as the recycled aggregate content increased.

[Insert figure 6 here].

The axial strains increased as the recycled aggregate replacement ratio increased, as observed in Figure (6). This agrees with some reference studies[24] and with the numerical study conducted using the finite element model described in the Numerical Modelling subsection.[25] Figure (7) presents the axial strains of the cylindrical specimens for the replacement ratios R0, R25, R50, R75, and R100.

[Insert figure 7 here].

Indirect Splitting Tensile Strength (Brazilian Test):

(ASTM C496/C496M-17)[26] was adopted to determine the splitting tensile strength at an age of 120 days. Two cylindrical specimens were tested for each replacement ratio of 0%, 25%, 50%, 75%, and 100%. The average failure load at which the cylinder split was recorded, and the splitting tensile

strength was calculated from Equation (1). The cylindrical specimens were also modelled for the same replacement ratios using ABAQUS.[25] The maximum load carried by each cylindrical specimen was obtained analytically and compared with the experimental value, as shown in Figure (8).

$$f_{sp} = \frac{2*P}{\pi*d*L} \qquad (1)$$

P: maximum load carried by the cylindrical specimen; d: diameter of the cylindrical specimen, d = 150 mm; L: length of the cylindrical specimen, L = 300 mm.

[Insert figure 8 here].

Table (5) presents the average splitting tensile stress values at 120 days; each value is the average of two specimens. The direct tensile strength values were calculated by multiplying by a factor of 0.85 in accordance with Ministry of Housing and Utilities.[19] The maximum load values from the analytical study were then taken, and Equation (1) was applied.

[Insert Table 5 here].

The table above shows a reduction in splitting tensile strength as the recycled aggregate replacement ratio increased. For the replacement ratios R25, R50, R75, and R100, the experimental reductions ranged from 15.4% to 25.8%, while the analytical reductions ranged from 7.8% to 26.7%, compared with the natural reference specimen (R0). The analytical splitting tensile strengths were higher than the experimental ones, by 5% to 16% depending on the mix, which is consistent with the reference study.[2,16]

Modulus of Elasticity (Ec) and Poisson's Ratio (μ):

The average modulus of elasticity (Ec) and average Poisson's ratio (μ) of the cylindrical specimens were determined. Poisson's ratio is the ratio of transverse strain to longitudinal strain when concrete is subjected to compressive stress within the elastic range, as shown in Figure (9)[27,28]

[Insert figure 9 here].

Table (6) presents the average modulus of elasticity (Ec) and average Poisson's ratio (μ) of the specimens at replacement ratios of 0%, 25%, 50%, 75%, and 100% at an age of 120 days.

[Insert Table 6 here].

The table above shows a decrease in the modulus of elasticity, Ec, as the recycled aggregate content increased. The reductions were 10.3%, 14.1%, 20.98%, and 26.95%, while Poisson's ratio (μ) increased by 5.17%, 5.75%, 6.9%, and 6.9%, respectively, with increasing recycled aggregate replacement ratios of R25, R50, R75, and R100, compared with concrete made with natural aggregate (R0).

The pronounced reduction in the modulus of elasticity of concrete containing recycled concrete aggregate (RCA) is associated with its increased deformability under structural loading. This behavior is primarily attributed to the presence of highly porous residual cement mortar adhered to the surfaces of the recycled aggregate particles, which increases the deformability of the concrete compared with concrete containing natural aggregate. Accordingly, an increase in the amount of residual mortar surrounding the aggregate particles leads to a greater reduction in the modulus of elasticity. This finding is consistent with those reported in several previous studies.[28–30]

Numerical Modelling:

To complement the experiments, the cylindrical specimens (150 × 300 mm) of each replacement level were modelled in ABAQUS/Standard v6.14-3[25] using a materially nonlinear finite element analysis. The concrete was meshed with eight-node three-dimensional solid elements (C3D8) and represented by the Concrete Damaged Plasticity (CDP) model, which combines isotropic damaged elasticity with tensile and compressive plasticity, describes failure through tensile cracking and compressive crushing, and accounts for the loss of elastic stiffness caused by plastic strains.[31] For each mix, the measured 120-day stress–strain curve, elastic modulus, and Poisson's ratio were used as input (Table 6). Compressive and tensile behaviour were defined by tabulated stress–inelastic strain data, and the stiffness degradation variables were computed as $d_c = (\sigma_{cu} - \sigma_c)/\sigma_{cu}$ in compression and $d_t = (\sigma_{t0} - \sigma_t)/\sigma_{t0}$

in tension.[32] The remaining plasticity parameters (Table 10) were taken from the ABAQUS documentation and previous studies: a dilation angle of 36°, an eccentricity of 0.1, f_{b0}/f_{c0} = 1.16, and K_c = 0.667, which modifies the Drucker–Prager yield criterion.[33,34] The viscosity parameter was set to 0.0005, close to zero, since values near zero have been reported to bring the numerical and experimental results close together.[35,36] The model was used to compare the axial strains and the maximum load of the cylinders with the experimental values. The numerical model of the cylindrical concrete specimen was developed with dimensions identical to those of the specimens used in the experimental tests. The specimen was subsequently discretized into a finite element mesh with an appropriate element size to achieve sufficient accuracy in representing the mechanical response while maintaining computational efficiency. To ensure consistency between the numerical model and the experimental setup, appropriate boundary conditions were applied to simulate the support and contact conditions of the specimen during testing, with the necessary degrees of freedom constrained to prevent unrealistic rigid-body motion. The loading conditions were also applied in accordance with the experimental loading procedure, such that the load was transferred to the specimen in a manner representative of the actual test conditions. This approach ensured a realistic numerical representation of the specimen's behavior and response under the applied loading.

[Insert Table 10 here].

Statistical Analysis:

Compressive strength was measured on three specimens per mix at 7 and 28 days, and the results are reported as mean ± standard deviation (SD, calculated with n − 1) together with the coefficient of variation (COV). The effect of the recycled aggregate replacement level (R0, R25, R50, R75 and R100) was evaluated separately at each age by one-way analysis of variance (ANOVA) at a significance level of $\alpha = 0.05$. Where ANOVA was significant, Tukey's honestly significant difference (HSD) test was used for pairwise comparisons between mixes. Homogeneity of variances was checked using the ratio of the largest to the smallest group variance (5.8 at 7 days and 2.1 at 28 days). With three specimens per

group, normality of the residuals could not be tested reliably, which is acknowledged as a limitation. The relationship between replacement level and compressive strength was examined by least-squares linear regression using all individual specimens (n = 15 per age).

Theoretical Evaluation of the Modulus of Elasticity

The experimental modulus of elasticity values were compared with theoretical values obtained from selected equations in internationally adopted codes, as follows:

Syrian Code (Ministry of Housing and Utilities)[19]:

The modulus of elasticity can be calculated from the following equation:

$$E_c = 5700 * \sqrt{f'_c} \qquad (2)$$

where the cylindrical compressive strength is expressed in MPa.

European Code (BS EN 1992)[37] :

The modulus of elasticity can be calculated from the following equation:

$$E_c = 22 * \left(\frac{f'_c}{10}\right)^{0.3} \qquad (3)$$

where the cylindrical compressive strength is expressed in MPa.

British Code (BS 8110, 1985)[18]:

The modulus of elasticity can be calculated from the following equation:

$$E_c = 1.7 * 10^{-6} * \rho^2 * f'c^{0.33} \qquad (4)$$

where:

the cylindrical compressive strength is expressed in MPa, and the unit weight is expressed in kg/m³.

American Code (ACI committee 318)[27]:

The modulus of elasticity can be calculated from the following equation:

$$E_c = 4700 * \sqrt{f'_c} \quad (5)$$

where the cylindrical compressive strength is expressed in MPa.

(Egyptian Code ECP-2017)[38]:

The modulus of elasticity can be calculated from the following equation:

$$E_c = 4400. \sqrt{f'_c} \quad (6)$$

where the cylindrical compressive strength is expressed in MPa.

Table (7) presents the modulus of elasticity values calculated using the equations of some of the above-mentioned codes and compares them with the experimental values, the cylindrical compressive strengths, and the unit weights listed in Table (4), for the replacement ratios R0, R25, R50, R75, and R100.

[Insert Table 7 here].

The table above shows that the modulus of elasticity calculated using ACI 318[27] and ECP-2017 was close to the experimental value for the natural aggregate concrete (R0), but both overestimated the modulus of the recycled aggregate concrete, with the overestimation increasing with the replacement ratio (up to about 28% and 20%, respectively, at R100). The other codes were less suitable, particularly the Syrian Code, which produced the highest values.

Proposed Equation for Calculating the Modulus of Elasticity:

Among the code equations compared (Table 7), the ACI 318 relationship (26.63 GPa) and the ECP-2017 relationship (24.93 GPa) were the closest to the measured modulus of the natural aggregate concrete (25.66 GPa); the ACI relationship was therefore adopted as the baseline model. For the mixes containing recycled aggregate, two empirical reduction factors were then introduced after several trials, one related to the compressive strength ratio and the other to the unit weight of the concrete:

$$E_{CR} = 4700 \cdot \sqrt{f'_c} \cdot \left(\frac{f'_c}{f'_{c0}}\right) \cdot \left[\frac{(\rho - 100)}{\rho 0}\right] \qquad (7)$$

where E_{CR} is the modulus of elasticity according to the proposed equation (MPa) f'_c and f'_{c0} are the cylindrical compressive strengths of the recycled and the natural aggregate concrete (MPa), respectively; and ρ and ρ0 are the corresponding unit weights (kg/m³). The constant 100 kg/m³ was obtained by trial and is purely empirical. Because the factor (ρ − 100)/ρ0 is below unity even for natural aggregate concrete (about 0.96 for ρ = 2,400 kg/m³), Eq. (7) predicts a modulus about 4% lower than the ACI relationship for R0. Equation (7) reproduced the measured moduli of the five mixes with differences between −3.6% and +2.5% (Table 8) and, when applied to the results of the reference studies, 9 of the 11 data points fell within ±15% of the reported experimental values (Table 9, Fig. 11). Since the coefficients were calibrated on the present data, the equation should be regarded as empirical and applied only within the range of the data (0–100% replacement and f'c of about 26–39 MPa).

[Insert Table 8 here].

Figure (10) presents plots of the modulus of elasticity values obtained using the codes mentioned above, the experimental values from this study, and the values obtained using the proposed equation. For concrete made with natural aggregate (R0), close agreement was observed among the experimental values, ACI 318, and ECP-2017. For concrete made with recycled aggregate, close agreement was observed between the experimental values and the proposed equation.

[Insert figure 10 here].

Comparison of the Proposed Equation with Results from Selected Reference Studies:

The proposed equation was applied to the results of several reference studies reviewed in this work to assess its accuracy and its agreement with the experimental results reported in those studies for calculating the modulus of elasticity.

Table (9) presents selected data from the reference studies, including compressive strength, unit weight, and replacement ratio. The modulus of elasticity was calculated using the proposed equation and compared with the experimental modulus of elasticity reported in the reference studies.

[Insert Table 9 here].

The modulus of elasticity values obtained from the proposed equation were compared with the actual experimental values reported by the reference studies. An acceptable range of ±15% from the experimental values was adopted using OriginPro,[39] as shown in Figure (11). Most of the points fall within the acceptable range, except for two cases. It should be noted that the equation gave lower values than the reported experimental moduli for 10 of the 11 data points (by up to 19.9%), i.e., it is conservative for these datasets. This indicates the validity of the proposed equation and its potential use for approximate prediction of the modulus of elasticity of recycled aggregate concrete.

It can be concluded that recycled aggregate has a clear effect on the modulus of elasticity of concrete, and the magnitude of this effect varies according to the quality of the recycled aggregate used and the design cylindrical compressive strength.

[Insert figure 11 here].

Results and Discussion

The experimental results of the study revealed the following:

1- The specific gravity of the recycled concrete aggregate (RCA) was lower than that of the natural aggregate. In addition, the bulk density decreased by 0.9–2.6% with increasing RCA content.

2- The cylindrical compressive strength decreased with increasing replacement of natural aggregate by recycled concrete aggregate. Compared with the reference concrete (R0), the reductions in compressive strength for mixtures R25, R50, R75, and R100 were 6.96%, 8.85%, 18.81%, and 20.50%, respectively, at 7 days; 6.51%, 9.93%, 15.70%, and 17.11%, respectively, at 28 days; and 3.80%, 7.60%, 13.30%, and 18.40%, respectively, at 120 days.

3- All mixtures exhibited an increase in cylindrical compressive strength with increasing concrete age. Compared with the compressive strength at 7 days, the increase at 28 days ranged from 42% to 50%, while the increase at 120 days ranged from 55% to 66%. Moreover, the increase between 28 and 120 days ranged from 6% to 11%.

4- The modulus of elasticity of concrete (Ec) decreased progressively with increasing RCA content. Compared with the reference concrete (R0), the reductions in the modulus of elasticity for mixtures R25, R50, R75, and R100 were approximately 10.3%, 14.1%, 20.98%, and 26.95%, respectively. Similarly, the splitting tensile strength decreased by 15.4%, 16.1%, 21.8%, and 25.8%, respectively.

5- Poisson's ratio increased by 5.17%, 5.75%, 6.90%, and 6.90% for mixtures R25, R50, R75, and R100, respectively, compared with the reference concrete (R0).

6- The finite element model (ABAQUS, concrete damaged plasticity) reproduced the increase in axial strain with increasing RCA content, and its splitting tensile strengths were 5% to 16% higher than the experimental values.

7- ACI 318 and ECP-2017 were the closest code equations to the measured modulus of elasticity of the natural aggregate concrete, but they overestimated that of the recycled aggregate concrete. The proposed equation reproduced the measured moduli within −3.6% to +2.5%, and 9 of the 11 data points from previous studies fell within ±15% of the reported values.

Statistical Analysis of Compressive Strength:

Table 11 and Fig. 12 summaries the compressive strength results. The coefficient of variation did not exceed 4.5% at 7 days or 3.8% at 28 days, indicating good repeatability of the tests. The mean compressive strength decreased from 20.67 MPa (R0) to 16.43 MPa (R100) at 7 days (a reduction of 20.5%) and from 29.81 MPa to 24.71 MPa at 28 days (a reduction of 17.1%). One-way ANOVA (Table

12) showed that the replacement level had a significant effect on compressive strength at both ages (7 days: $F(4,10) = 20.87$, $p < 0.001$, $\eta^2 = 0.89$; 28 days: $F(4,10) = 18.47$, $p < 0.001$, $\eta^2 = 0.88$).

[Insert Table 11 here].

[Insert Figure 12 here].

[Insert Table 12 here].

Tukey's HSD test showed that the 25% replacement did not significantly change the compressive strength relative to the control mix at either age ($p = 0.137$ at 7 days and $p = 0.101$ at 28 days), despite mean reductions of 7.0% and 6.5%, respectively. A significant reduction relative to R0 first appeared at 50% replacement ($p = 0.047$ at 7 days, which is marginal, and $p = 0.010$ at 28 days) and became more pronounced at 75% and 100% replacement ($p \leq 0.0003$ at both ages). R75 and R100 were not significantly different from each other ($p = 0.966$ at 7 days and $p = 0.971$ at 28 days), indicating that increasing the replacement from 75% to 100% did not further reduce the strength within the precision of the tests.

Linear regression showed a decrease of approximately 0.044 MPa at 7 days and 0.052 MPa at 28 days per 1% of recycled aggregate replacement ($R^2 = 0.85$ at both ages, $p < 0.001$).

Conclusions

Based on the experimental and analytical results, the following conclusions can be drawn:

1- Replacing natural aggregate with recycled concrete aggregate (RCA) reduced the unit weight of the concrete by 0.9–2.6%, owing to the lower specific gravity and bulk density of the recycled aggregate.

2- The cylindrical compressive strength decreased progressively with increasing RCA content (by 7.0–20.5% at 7 days, 6.5–17.1% at 28 days, and 3.8–18.4% at 120 days), while the strength continued to develop with age. ANOVA confirmed a significant effect of the replacement level

at 7 and 28 days ($p < 0.001$). Tukey's test showed that the 25% replacement did not differ significantly from the reference concrete, that significant reductions appeared from 50% replacement (marginally at 7 days), and that R75 and R100 were not significantly different from each other.

3- The modulus of elasticity decreased by 10.3–26.95% and Poisson's ratio increased by 5.2–6.9% as the replacement level increased. At 120 days, the reduction in modulus of elasticity (10.3–26.95%) was larger than the reduction in compressive strength (3.8–18.4%), so the deformation properties are more sensitive to RCA than the strength.

4- The splitting tensile strength decreased by 15.4–25.8%, and the reduction became more pronounced at higher replacement levels.

5- The ABAQUS model (concrete damaged plasticity) reproduced the increase in axial strain with increasing RCA content, and its splitting tensile strengths were 5–16% higher than the experimental values.

6- ACI 318 and ECP-2017 were the closest code equations to the measured modulus of elasticity of the natural aggregate concrete but overestimated that of the recycled aggregate concrete (by up to about 28% and 20% at R100), and the Syrian Code gave the highest values.

7- The proposed equation, based on the ACI 318 relationship with reduction factors for the compressive strength ratio and the unit weight, reproduced the measured moduli within −3.6% to +2.5%, and 9 of 11 data points from previous studies fell within ±15%. It is empirical, was calibrated on the present data (0–100% replacement, f'c of about 26–39 MPa), and tends to be conservative for the reference data, so it should be applied only within this range.

8- Larger numbers of specimens per mix, other qualities of recycled aggregate, and additional independent datasets are needed to confirm the proposed equation and the statistical conclusions.

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author, Manar Takla, upon reasonable request.

Author Contributions

F.M. and M.T. contributed to the study design and development of the research approach. F.M., M.T., H.A.K. and I.T. contributed to interpretation of the findings and revision of the manuscript. All authors reviewed the manuscript.

Additional Information

Competing interests

The authors declare no competing interests.

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Table 1. Physical and mechanical properties of natural and recycled aggregate 585

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Physical and Mechanical Properties	Natural Aggregate			Recycled Aggregate		
	Coarse Gravel	Fine Gravel	Crushed Sand	Coarse Gravel	Fine Gravel	Crushed Sand
Oven-Dry Specific Gravity	2.61	2.6	2.64	2.37	2.38	2.57
Saturated Surface-Dry Specific Gravity	2.64	2.66	2.68	2.47	2.49	2.63
Apparent Specific Gravity	2.71	2.70	2.72	2.69	2.68	2.7
Los Angeles Abrasion Loss (%)	20.13		-	31.53		-
Absorption (%)	2.16		-	5.11		-
Sand Equivalent (E.S.) (%)	71.4					

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Table 2. Masses of materials used in the study per cubic meter

Aggregate Type	Unit	Recycled Aggregate Replacement (%)				
		R0	R25	R50	R75	R100
Natural Coarse Gravel	Kg/m³	722.09	541.57	361.05	180.52	-
Natural Fine Gravel	Kg/m³	453.22	339.92	226.61	113.31	-
Natural Crushed Sand	Kg/m³	521.63	391.22	260.82	130.41	-
Recycled Coarse Gravel	Kg/m³	-	132.49	264.98	397.47	529.96
Recycled Fine Gravel	Kg/m³	-	160.88	321.76	482.64	643.52
Recycled Crushed Sand	Kg/m³	-	97.64	195.28	292.91	390.55
Fine Sand	Kg/m³	234.02	252.02	270.03	288.03	306.03
Type I Cement	Kg/m³	400	400	400	400	400
Water	Kg/m³	200	200	200	200	200
Water–Cement Ratio w/c	%	50%	50%	50%	50%	50%

Table 3. Average failure load and average compressive strength at 7 and 28 days

Mix ID	7 days		28 days	
	Load (kN)P	Cylindrical Compressive Strength	Load (kN)P	Cylindrical Compressive Strength
R0	365.3	20.67	526.8	29.81
R25	339.8	19.23	492.5	27.87
R50	332.9	18.84	474.5	26.85
R75	296.5	16.78	444.1	25.13
R100	290.3	16.43	436.7	24.71

Table 4. Average mass, unit weight, failure load, and cylindrical compressive strength at120 days

Mix ID	120 days			
	Weight W (kg)	Unit weight ρ (Kg/m³)	Load (kN)P	Cylindrical Compressive Strength (MPa)
R0	12.71	2397.46	567.4	32.11
R25	12.6	2376.71	545.9	30.89
R50	12.56	2369.17	524.1	29.66
R75	12.45	2348.42	491.8	27.83
R100	12.38	2335.22	463	26.2

Table 5. Load, splitting tensile stress, and experimental and analytical tensile strength values

Mix ID	Experimental EXP			Analytical EFM		
	Load (kN)	Splitting Tensile Strength (MPa)	Tensile Strength (MPa)	Load (kN)	Splitting Tensile Strength (MPa)	Tensile Strength (MPa)
R0	210.9	2.98	2.54	224.8	3.18	2.7
R25	178.4	2.52	2.14	207.1	2.93	2.49
R50	177	2.5	2.13	193.4	2.74	2.33
R75	164.8	2.33	1.98	176.5	2.50	2.12
R100	156	2.21	1.88	164.5	2.33	1.98

Table 6. Modulus of elasticity and Poisson's ratio values of the specimens

Mix ID	120 days	
	Modulus of Elasticity Ec (MPa)	Poisson's Ratio
R0	25664.91	0.174
R25	23012.15	0.183
R50	22050.33	0.184
R75	20280.13	0.186
R100	18748	0.186

Table 7.Experimental and theoretical modulus of elasticity values according to selected codes

Code / Group	Ec (GPa)					
Group	Syrian	American ACI-318	British BS-8110	European BS EN -1	Egyptian ECP	Experimental Values
R0	32.30	26.63	30.70	31.22	24.93	25.66
R25	31.68	26.12	29.79	30.86	24.46	23.01
R50	31.04	25.60	29.20	30.48	23.96	22.05
R75	30.07	24.80	28.10	29.91	23.21	20.28
R100	29.18	24.06	27.24	29.37	22.52	18.75

Table 8. Comparison of modulus of elasticity values obtained using the proposed equation with experimental values

Mix ID Group	Replacement (%)	Modulus of Elasticity Ec (GPa)		Percentage Difference (%)
		Study Results	Proposed Equation Results	
R0	0	25.66	25.52	0.55
R25	25	23.01	23.87	-3.58
R50	50	22.05	22.37	-1.44
R75	75	20.28	20.16	0.62
R100	100	18.75	18.30	2.45

Table 9. Comparison of experimental modulus of elasticity with modulus of elasticity calculated using the proposed equation for selected studies

Reference Study	Replacement (%)	Unit Weight (kg/m³)	Average Cylindrical Compressive Strength (MPa)	Experimental Modulus of Elasticity (GPa)	Modulus of Elasticity by Proposed Equation (GPa)	Difference (%)
Kou[40]	0	2315	38.88	30	28.04	6.53
	20	2298	36.24	28.8	25.04	13.06
	50	2274	34	26.3	22.51	14.43
	100	2265	30.48	21.7	19.02	12.33
Paul[41]	0	2427	37.26	31.75	27.51	13.36
	30	2420	37.77	33.2	27.99	15.69
	100	2335	33.94	26.8	22.97	14.30
Corinaldesi[42]	0	2262	35.12	28	26.62	4.92
	30	2230	27.76	23	18.43	19.86
Gupta et al.[43]	0	2349	30.4	22.6	24.81	-9.78
	100	2245	26.4	19.3	19.15	0.78

Table 10. Concrete damaged plasticity (CDP) parameters used in the ABAQUS model.

Parameter	**Value**
Dilation angle (°)	36
Eccentricity	0.1
f_{b0} / f_{c0} (biaxial to uniaxial compressive strength)	1.16
K_c (yield surface shape factor)	0.667
Viscosity parameter	0.0005

Source of the values: ABAQUS documentation and the references cited in the text.

Table 11. Compressive strength (mean ± SD, n = 3), coefficient of variation (COV) and Tukey HSD grouping of the mixes.

Mix	fc 7 d (MPa)	COV (%)	fc 28 d (MPa)	COV (%)	Change vs R0 at 28 d (%)
R0	20.67 ± 0.90 (a)	4.3	29.81 ± 0.94 (a)	3.1	—
R25	19.23 ± 0.37 (ab)	1.9	27.87 ± 0.65 (ab)	2.3	-6.5
R50	18.84 ± 0.57 (b)	3.0	26.85 ± 0.94 (bc)	3.5	-10.0
R75	16.78 ± 0.67 (c)	4.0	25.13 ± 0.69 (c)	2.7	-15.7
R100	16.43 ± 0.73 (c)	4.5	24.71 ± 0.94 (c)	3.8	-17.1

Within each age, means sharing the same letter are not significantly different (Tukey HSD, $p < 0.05$). fc, compressive strength.

Table 12. One-way ANOVA of compressive strength with respect to replacement level.

Age	Source	SS	df	MS	*F*	*p*
7 days	Between groups	37.53	4	9.38	20.87	< 0.001
	Within groups	4.49	10	0.45		
28 days	Between groups	52.06	4	13.02	18.47	< 0.001
	Within groups	7.05	10	0.70		

SS, sum of squares; df, degrees of freedom; MS, mean square.

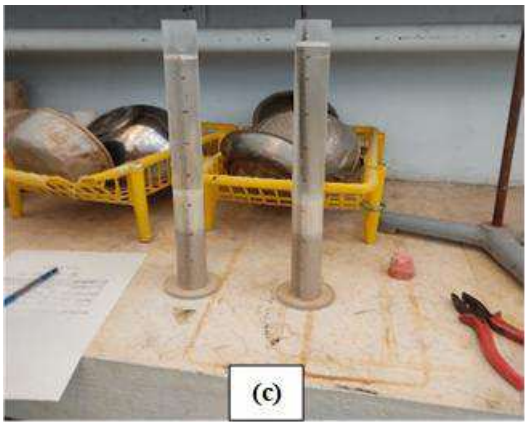


Fig. 1. Photograph of the crusher used and the aggregate after crushing and screening

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(a): Specific gravity test. (b): Los Angeles abrasion test. (c): Sand equivalent test. 645

Fig. 2. Tools, materials, and equipment used to conduct the three tests. 646

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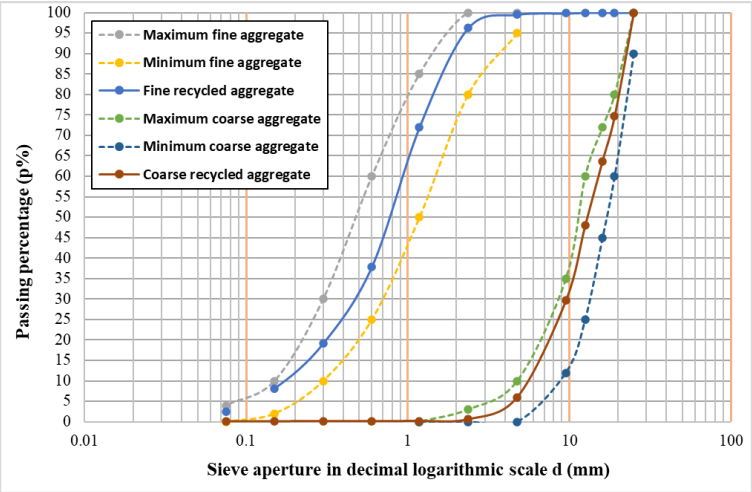


Fig. 3. Particle size distribution of the recycled aggregate mixtures used in the study.

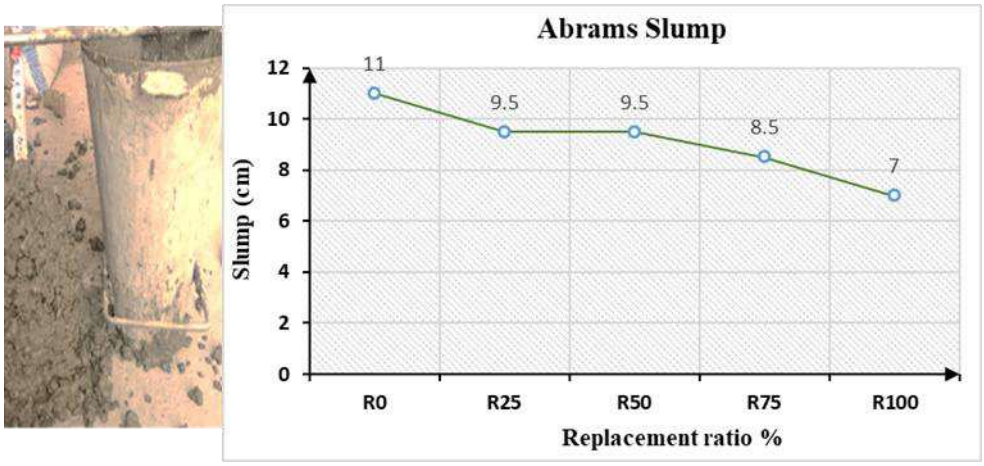


Fig. 4. Abrams slump values at different replacement ratios



(a): Measurement of the dimensions and masses of the cylindrical specimens. (b): Specimen in the testing machine. (c): Failure mode of the cylindrical specimens.

Fig. 5. Compression test and testing machine

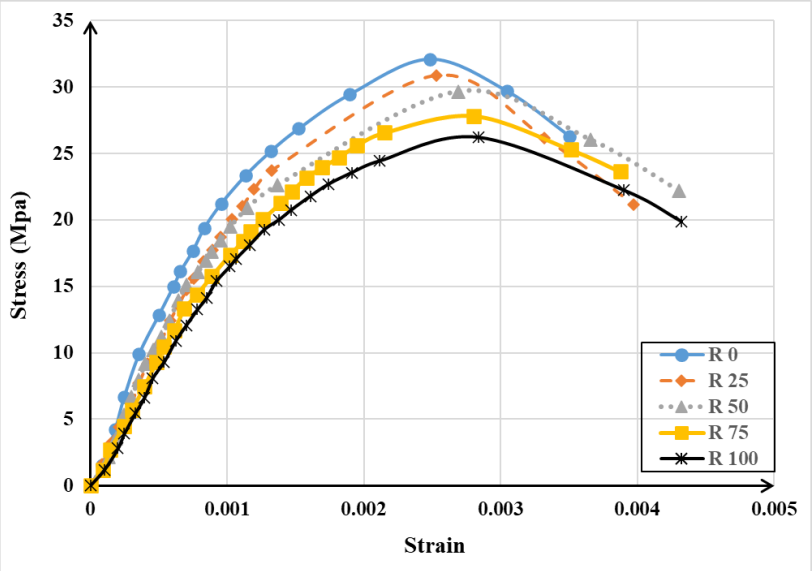


Fig. 6. Stress–strain curves for replacement ratios of R0, R25, R50, R75 and R100

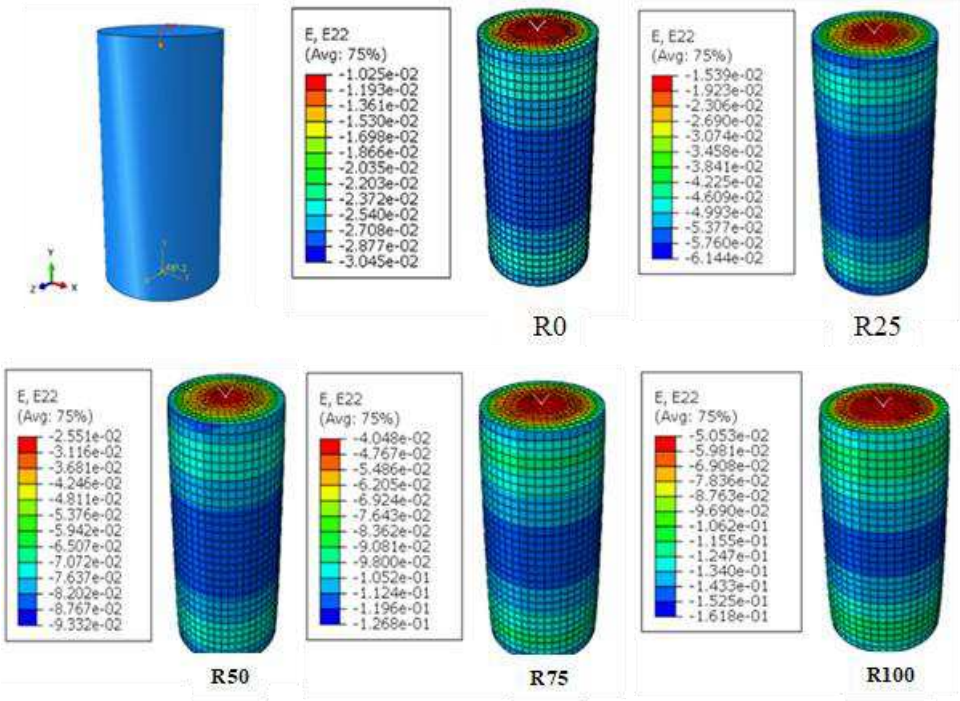


Fig. 7. Analytical axial strains of the specimens at the stated replacement ratios

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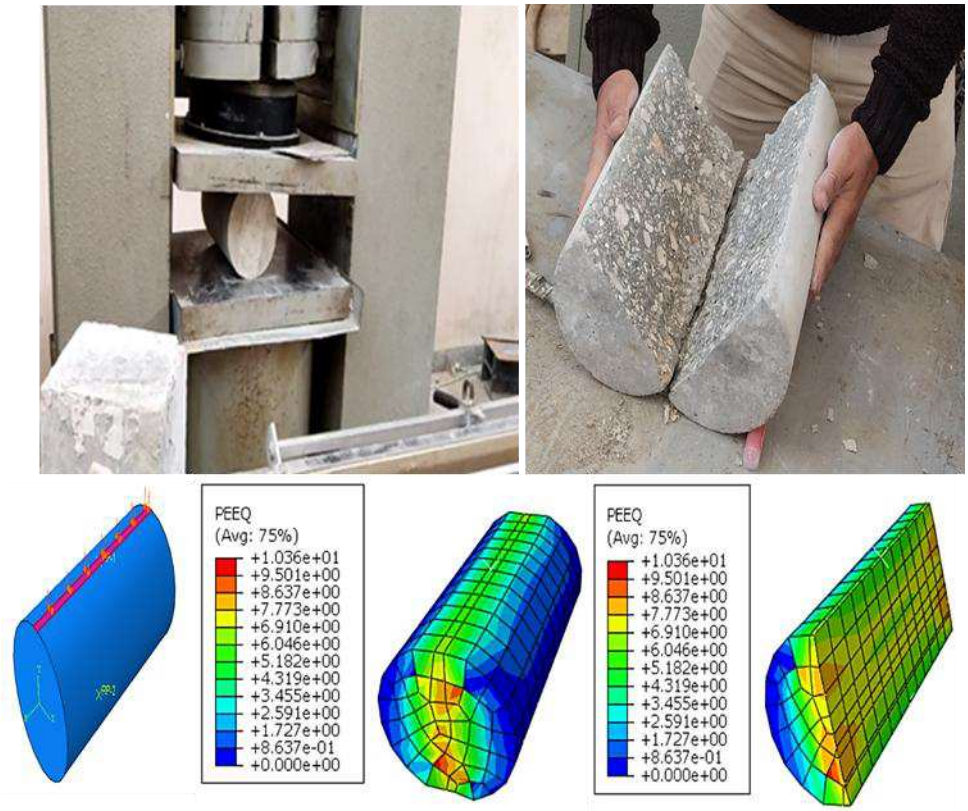


Fig. 8. Testing machine for determining tensile strength, cylindrical specimen, and crack distribution 674

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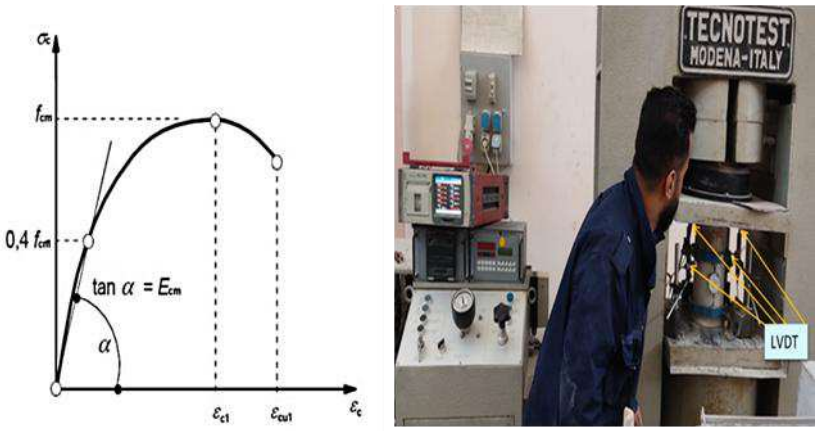


Fig. 9. Stress–strain curve according to the codes and testing machine in the concrete laboratory.

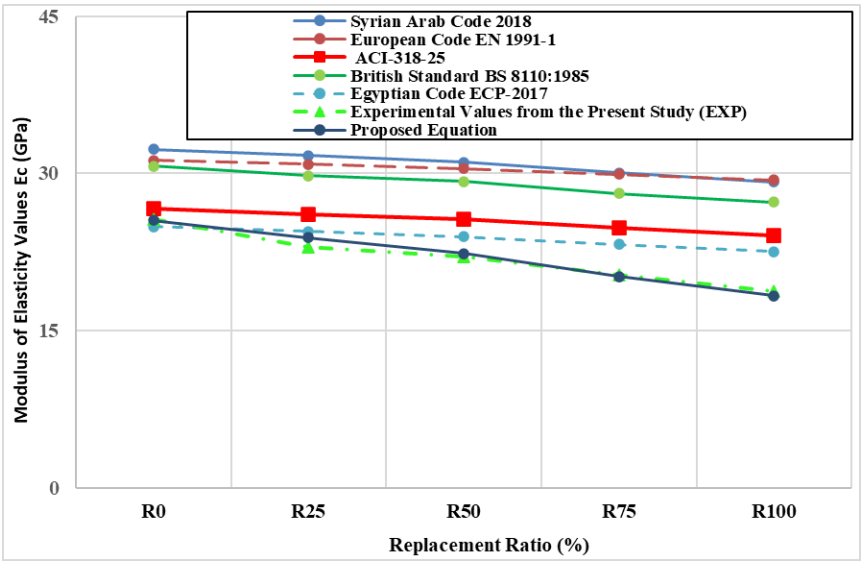


Fig. 10. Modulus of elasticity values for the study variables and selected codes

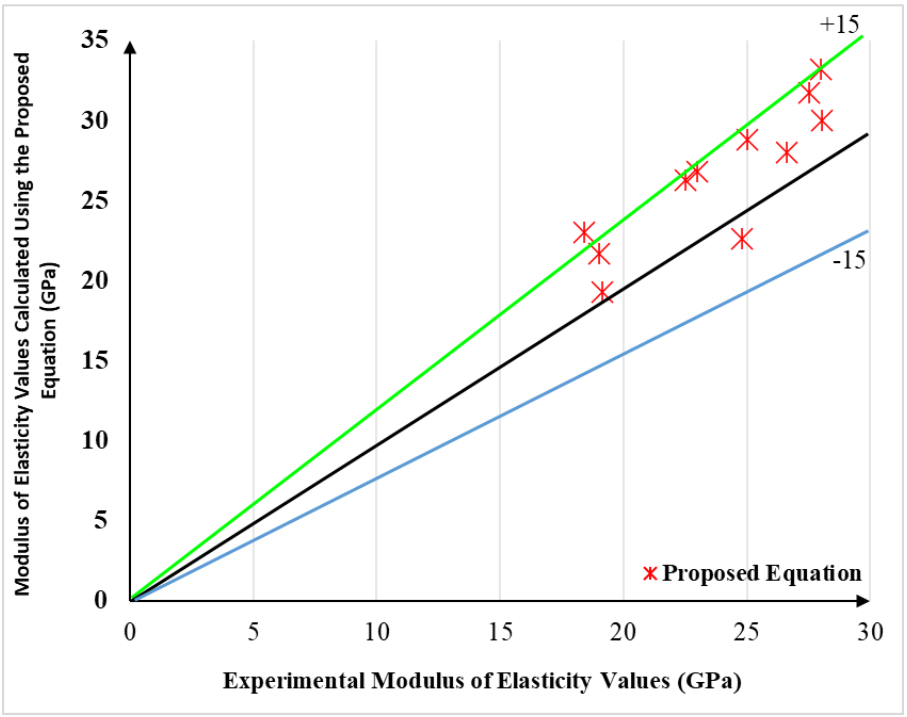


Fig. 11. Comparison of experimental values from previous studies with values obtained from the proposed equation within the ±15% range

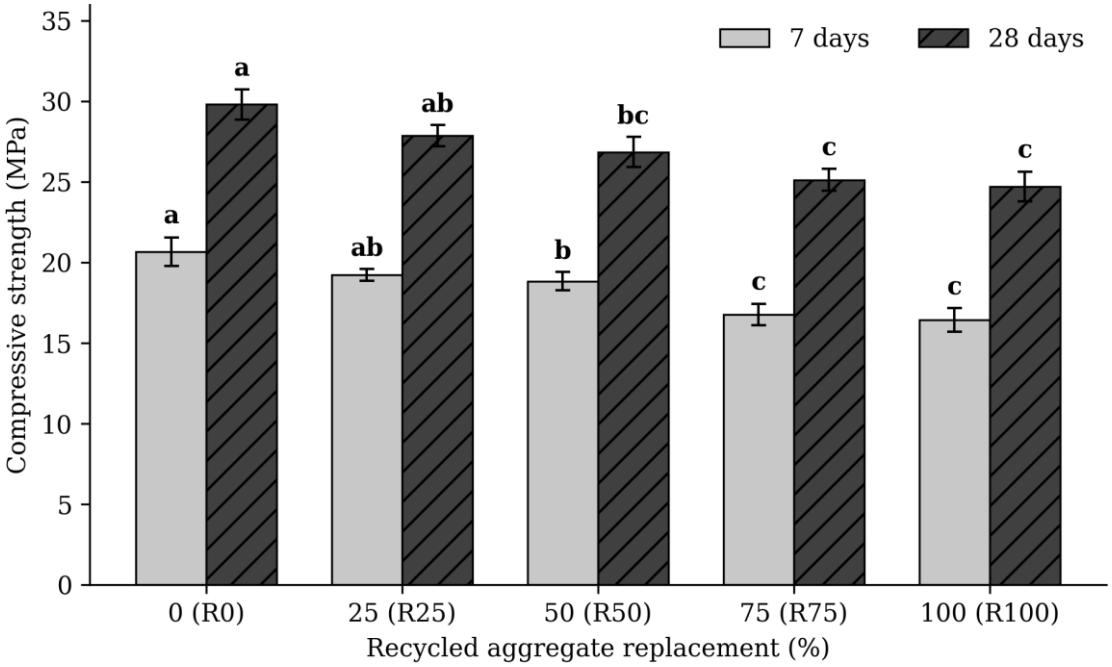


Fig. 12. Compressive strength at 7 and 28 days versus recycled aggregate replacement level. Error bars represent ± 1 SD (n = 3). Within each age, bars sharing the same letter are not significantly different (Tukey HSD, $p < 0.05$).