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The Effect of Compression Casting Technique on Epoxy Polymer Concrete Using Recycled Coarse Aggregate

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Abstract

Background: Recycled coarse aggregate (RCA) in epoxy polymer concrete supports sustainable construction; however, adhered old mortar increases porosity and heterogeneity, which may weaken stress transfer and accelerate damage.
Objective: This study evaluates the effect of compression casting on the physical and mechanical properties of 100% RCA-based epoxy polymer concrete, focusing on compressive strength, water absorption, and specific gravity of cube specimens.
Methods: A semi-dry mixture was prepared using Bisphenol-A epoxy resin, a cycloaliphatic amine hardener, and Type C fly ash as filler. Cube specimens measuring 50 × 50 × 50 mm were cast under four pressure levels (0.00, 3.60, 4.80, and 6.00 MPa), with three replicates for each level. Compressive strength, water absorption, and specific gravity were tested in accordance with ASTM C579 (Method B), ASTM C413 (Method B), and ASTM D792, respectively.
Results: Compression casting improved material densification. Compressive strength increased from 33.754 MPa without compaction to 57.426 MPa at 3.60 MPa and peaked at 60.190 MPa at 4.80 MPa, before decreasing to 54.009 MPa at 6.00 MPa. Water absorption decreased to 0.216%, while specific gravity increased to 2.309 g/cm^3 at 6.00 MPa.
Conclusion: The optimal pressure for maximizing compressive strength was 4.80 MPa, while 6.00 MPa produced the highest physical densification.

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INTRODUCTION

The construction industry increasingly requires materials that can meet structural performance demands while also supporting environmental sustainability. The use of recycled coarse aggregate (RCA) obtained from construction and demolition waste can reduce the exploitation of natural aggregates and provide a practical pathway for material reuse in construction (Carrión *et al.*, 2014; Wang *et al.*, 2022). The utilization of RCA is also consistent with circular economy principles, which are receiving increasing attention in the development of sustainable construction materials (Kryeziu *et al.*, 2023) However, the use of RCA still presents several technical challenges because adhered old mortar on its surface tends to increase porosity, water absorption, and material heterogeneity, which may adversely affect concrete performance (McNeil & Kang, 2013; Muhammad *et al.*, 2024).

Epoxy-based polymer concrete is a composite material in which Portland cement is replaced by a thermosetting resin matrix that binds aggregates and fillers into a dense solid system (Abdel-Fattah & El-Hawary, 1999; Salami *et al.*, 2024). This material has attracted attention because of its high mechanical strength, strong adhesion, chemical resistance, low permeability, and relatively rapid curing, making it suitable for structural and semi-structural applications such as repair materials, precast components, industrial floors, and chemically resistant construction products (Bedi *et al.*, 2013; Salami *et al.*, 2024; Smoleń *et al.*, 2024). However, the performance of polymer concrete is highly dependent on the quality of the polymer matrix, aggregate packing, and internal void (Haidar *et al.*, 2011; Ferdous *et al.*, 2020; Smoleń *et al.*, 2024). Entrapped air, microvoids, and non-uniform resin distribution can interrupt stress transfer, create local stress concentrations, and reduce compressive strength (Haidar *et al.*, 2011; Rochman *et al.*, 2023; Palamarchuk *et al.*, 2024). Therefore, improving the internal densification of epoxy polymer concrete is essential, particularly when recycled coarse aggregate is used as the main aggregate phase because RCA commonly contains adhered old mortar, higher porosity, and greater absorption than natural aggregate (McNeil & Kang, 2013; Kryeziu *et al.*, 2023; Muhammad *et al.*, 2024).

The combination of RCA and epoxy polymer concrete requires a specific scientific rationale because both systems are sensitive to internal defects and porosity. RCA commonly contains adhered old mortar, higher absorption, and microcracks, which can increase material heterogeneity and reduce the mechanical reliability of concrete (McNeil & Kang, 2013; Kryeziu *et al.*, 2023; Muhammad *et al.*, 2024). However, in an epoxy polymer concrete system, the porous and rough surface of RCA may also provide a favorable substrate for resin adhesion, surface coating, and mechanical interlocking when the mixture is properly designed (Carrión *et al.*, 2014; Ferdous *et al.*, 2020; Salami *et al.*, 2024). Kępniak *et al.* (2024) reported that the improved performance of polymer concrete with recycled aggregate may be associated with the formation of a coating layer around recycled aggregate particles, in which resin and fine mineral particles help fill surface pores and improve the aggregate–matrix interface. The epoxy matrix has strong bonding capability, relatively low permeability, and good aggregate-coating ability, so it may partially compensate for the weaknesses of RCA by filling surface pores and improving the continuity of the aggregate–matrix interface (Ferdous *et al.*, 2020; Palamarchuk *et al.*, 2024). In addition, Type C fly ash can function as a fine mineral filler that improves particle packing, reduces microvoids, and modifies the resin–filler structure within polymer-based composites (Rochman, *et al.*, 2023; Rochman, *et al.*, 2023). Therefore, the combination of RCA, epoxy resin, fly ash, and compression casting is expected to produce a denser composite structure with improved stress transfer, lower absorption, higher specific gravity, and enhanced compressive strength (Nematzadeh & Naghipour, 2012b, 2012a; Hameed *et al.*, 2023).

Compression casting of fresh concrete mixtures has been explored as a processing strategy to address problems related to voids, insufficient compaction, and non-uniform particle arrangement. Previous studies on cement-based concrete and recycled aggregate concrete have shown that fresh-state compression can increase material density, reduce void volume, and improve microstructural quality (Justs *et al.*, 2013; Nematzadeh *et al.*, 2016; Liang *et al.*, 2022; Nemati *et al.*, 2023). In polymer concrete, this method is expected to improve the aggregate–filler–resin system by enhancing particle contact, reducing entrapped air, and producing a more compact internal structure. Salami *et al.* (2024) also emphasized that polymer matrix distribution and densification degree are important factors governing the final performance of polymer concrete.

Previous studies have extensively discussed the use of RCA in cement-based concrete, particularly its effects on porosity, water absorption, adhered mortar, and mechanical performance (McNeil & Kang, 2013; Kryeziu *et al.*, 2023; Muhammad *et al.*, 2024). Other studies have examined polymer concrete as a resin-based composite material with high mechanical strength, low permeability, chemical resistance, and strong dependence on matrix quality and internal void structure (Ferdous *et al.*, 2020; Salami *et al.*, 2024; Smoleń *et al.*, 2024). In addition, fresh concrete compression and compression casting techniques have been reported to improve density, reduce voids, and enhance mechanical performance in cement-based concrete and recycled aggregate concrete systems (Wang *et al.*, 2022; Hameed *et al.*, 2023; Nemati *et al.*, 2023). However, the combined use of compression casting as a processing strategy for epoxy polymer concrete incorporating 100% RCA remains insufficiently clarified. This gap is important because the performance of RCA-based epoxy polymer concrete depends not only on the intrinsic properties of RCA or epoxy resin, but also on the degree of densification, resin distribution, aggregate packing, and connected void reduction during the fresh-state forming process (Haidar *et al.*, 2011; Ferdous *et al.*, 2020; Palamarchuk *et al.*, 2024). Therefore, this study evaluates the effect of compression casting pressure on the physical and mechanical performance of epoxy polymer concrete incorporating 100% RCA, with a specific focus on compressive strength, water absorption, and specific gravity.

METHOD

Materials and Mix Composition

The coarse aggregate used in this study was 100% Recycled Coarse Aggregate (RCA) obtained from crushing concrete cylinders with an initial quality of $f_c' \geq 30$ MPa. The RCA was then sieved to have a maximum nominal size of 10 mm. Before use, the RCA was cleaned using running water and dried in an oven without additional pre-treatment. The fine aggregate used was natural river sand from Lumajang with a gradation predominantly passing the No. 8 sieve (2.36 mm). The concrete mixture was given an additive of Type C Fly ash meeting ASTM C618−19 criteria, which functions as a mineral filler. Table 1 presents the results of material characteristic testing used as a basis for mix design and interpretation of the physical-mechanical behavior of the resulting polymer concrete.

Table 1. Test Results for Aggregates and Fly Ash

Test	Unit	Sand (Lumajang)	Crushed Stone (RCA <19 mm)	Fly Ash Type C
Gradation		Zone 2	-	-
Oven Dry Specific Gravity	(g/cm^3)	2.696	2.313	2.500
SSD Specific Gravity	(g/cm^3)	2.714	2.459	-
Absorption	(%)	0.654	6.309	-
Moisture Content	(%)	4.706	4.861	-
Hardness	(%)	-	13.686	-

The polymer binder system consisted of liquid bisphenol-A epoxy resin (Bakelite® EPR 174) and a cycloaliphatic amine hardener (Bakelite® EPH 555). The selection of epoxy resin was based on its properties of high adhesion, good mechanical properties, and relatively low curing shrinkage, making it suitable as a binding matrix for aggregate-based composite systems (Zhang *et al.*, 2022; Shi *et al.*, 2024). Table 2 presents the technical specifications of the resin and hardener used to verify that the chosen resin-hardener volume ratio is very appropriate for the stoichiometric balance.

Table 2. Technical Specifications of the Polymer System

Examination	*Epoxy Resin*	*Hardener*
	Bisphenol-A	**Cycloaliphatic Amine**
Viscosity at 25 °C	13.0 ± 2.0 mPa·s	0.5 – 1.0 poise
Epoxy Equivalent	189 ± 5 g/equiv.	-
Epoxy Value	0.53 equiv./100 g	-
Active Hydrogen Equivalent	-	86 g/equiv.
Amine Value	-	325 Mg KOH/g
Density at 25 °C	1.17 ± 0.01 g/cm^3	1.010 g/cm^3

This study deliberately used a base mixture with a semi-dry consistency, as this condition is considered more stable during the molding process and allows for better control of experimental parameters during the application of compression casting (Liu *et al.*, 2022; Martin, 2024). Table 3 shows the mass fractions of the cube specimen mixture. The composition of the mixture was calculated based on the volume fraction of each material; this volume was then converted into weight units (grams) through specific gravity. Table 4. presents that during the fresh concrete phase, the compression level was divided into four categories, denoted as Cu. N (±0.00 MPa), Cu. L (±3.60 MPa), Cu. M (±4.80 MPa), and Cu. H (±6.00 MPa). Three cube specimens were produced at each compression level for creating a testing matrix to comparative evaluate the effect of mechanical densification on specific gravity, absorption and compressive strength.

Table 3. Mix Design for Cube Specimens in Weight (grams)

Specimen	Resin[b]	*Hardener*[c]	Coarse Agr.[d]	Fine Agr.[e]	*Fly Ash*[f]
Cube	19.31	11.11	90.16	169.17	27.50

[a] Mixture proportions based on material volume proportion × material specific gravity
[b] Specific gravity of EPR 174 = 1.170 g/cm^3
[c] Specific gravity of EPH 555 = 1.010 g/cm^3
[d] Specific gravity of recycled coarse aggregate = 2.459 g/cm^3
[e] Specific gravity of fine aggregate = 2.714 g/cm^3
[f] Specific gravity of fly ash = 2.500 g/cm^3

Table 4. Experimental Matrix of Compression Casting Levels

Description	Code	*n*	*Compression Level (MPa)*	Area (mm^2)	Load (kN)
Non Compression[a]	Cu.N	3	±0.00	2500	0.00
Low Compression	Cu.L	3	±3.60	2500	9.00
Medium Compression	Cu.M	3	±4.80	2500	12.00
High Compression	Cu.H	3	±6.00	2500	15.00

[a] Used as a control specimen

The experimental matrix was designed to isolate the effect of compression casting pressure on a fixed RCA-based epoxy polymer concrete system. Therefore, the non-compressed mixture (Cu.N, ±0.00 MPa) was used as the control group, while Cu.L, Cu.M, and Cu.H represented the same mixture subjected to different initial compression pressures. No natural coarse aggregate polymer concrete or OPC-based RCA concrete was included because the objective of this study was not to compare aggregate substitution or binder systems, but to evaluate the effectiveness of compression casting as a fresh-state densification technique for epoxy polymer concrete incorporating 100% RCA and Type C fly ash. This design allows the influence of compaction pressure to be examined while maintaining constant material composition, binder type, RCA content, and fly ash content across all groups.

Figure 1. Constituent Materials of Polymer Concrete

Preparation of Cube Specimens

Cube specimens were prepared according to ASTM C579 Method B, frequently employed for polymer concrete containing aggregate size of up to 10 mm. Weighing of all constituent materials (sand, RCA and fly ash) as per the mix proportions has been carried out. To keep the mix ratio accurate, the polymer binder system containing EPR 174 as well as EPH 555 was prepared accurately with a syringe. First, the mixing process started with about two minutes of solid phase homogenization, followed by the addition of resin and hardener to the dry blend and stirring for 8 min until a homogenous mixture was obtained.

Concrete cubes of 50 × 50 × 50 mm cubicle molds are filled in three equivalent volume layers with the fresh mixture. Each layer was consolidated with 25 evenly distributed stabs across the entire cross-section in the non-compacted control group. On the other hand, for the compressed group, consolidation was executed mechanically with a compression machine as specified in the experimental design to specific pressure levels. The mold was designed with additional headspace to accommodate volume reduction due to compression. After each layer was leveled, the mixture surface was covered with a load distribution plate and pressed controllably for ±2 minutes before the next layer was filled (Nematzadeh & Naghipour, 2012a, 2012b; Wang *et al.*, 2022).

Figure 2. Mixing of Polymer Concrete (Left) and Condition of Concrete After Curing (Right)

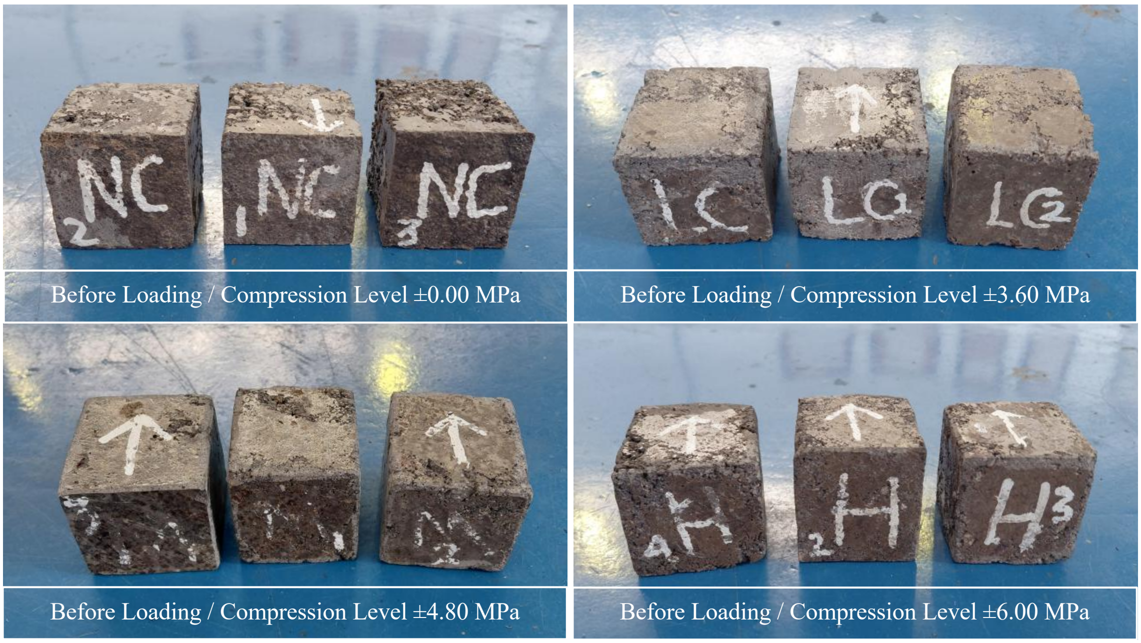

Figure 3. Visualization of Cube Specimens at Each Compression Level

After the last layer was compacted, the remaining mixture was poured, and the top surface of the specimen was leveled flush with the mold boundaries. The initial polymerization process was carried out thermally by placing the specimens in an oven at approximately 80 °C for 8 hours (Lascano *et al.*, 2019). During this stage, the test specimens remained in the mold to prevent early deformation while the material had not yet achieved adequate stiffness. After demolding, the specimens were immersed in room temperature water for 24 hours, then left in laboratory conditions for 28 days before physical and mechanical testing. These stages were intended to ensure that the specimens had reached a stable condition before absorption and compressive strength testing were carried out.

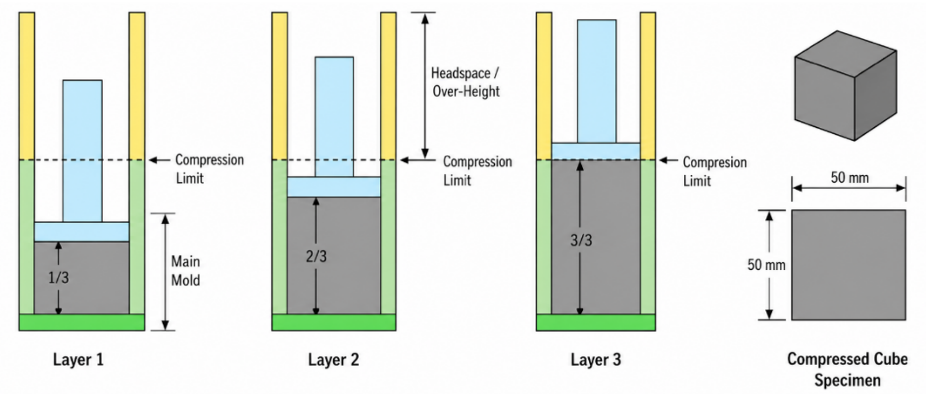

Figure 4. Mold Concept & Work Plan for Compressed Test Specimens

Water Absorption Testing

Absorption testing was conducted to evaluate the ability of polymer concrete to absorb water as an indirect indicator of interconnected voids and the quality of internal material densification. The test specimens were conditioned at controlled room temperature to a constant dry mass, weighed to determine their initial dry weight (W_d), before testing. This step is carried out in order to ensure that the change in mass measured at the end of test represents an actual uptake of water by the material, rather than variations in surface moisture content or remnants of humidity due to storage.

Figure 5. Boiling Process for Absorption Test Specimens

Subsequently, the specimens were soaked in a container with distilled water and boiled for 2 hours to speed up saturation, followed by a gradual cooling process within the same medium until they reached room temperature. Thereafter, specimens were dried externally with wet cloth wiping out the free water but not affect the water possibly invaded in pores, followed by reweighed to determine the saturated weight (W_s). Absorption value was determined gravimetrically according to ASTM C413 Method B, which is used for polymer concrete with aggregate size of 1.610 mm–10 mm. The maths for this calculation is set out in the below equation:

$$A = \frac{W_s - W_d}{W_d} \times 100$$

Where:
A_{abs} = Water Absorption (%)
W_s = Saturated Weight of Test Specimen (g)
W_d = Dry Weight of Test Specimen (g)

To be interpretative, a low absorption value tends to tend towards a denser fine structure of the internal structure and fewer connecting voids by volume; on the other hand, a high absorption value indicates a higher number of fluid penetration pathways within the material. The content of mortar on the recycled aggregates constitutes a parameter of great importance for RCA-based polymer concrete, since old mortar tends to increase the aggregate porosity and water absorption.

Specific Gravity Testing

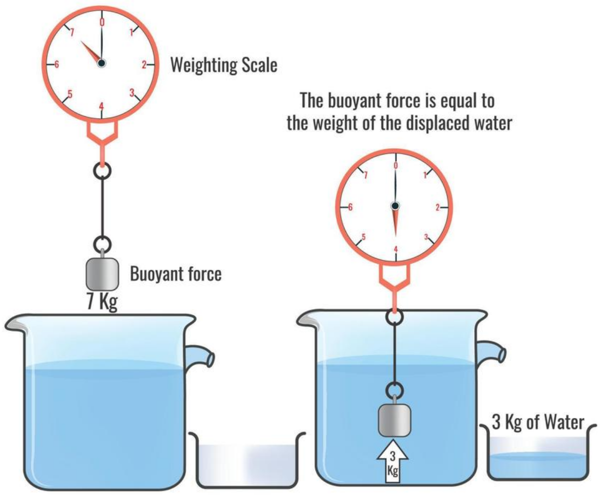

Figure 6. Schematic of Archimedes' Law
Source: Nandalal Sarkar (https://www.vecteezy.com/vector-art/20240706)

The specific gravity of the cube specimens was measured through a hydrostatic method applied using Archimedes' principle, i.e., weighing the test specimen in air and its suspension in water. It was found that a more realistic estimate of the true specimen volume can often be calculated from an immersion method rather than using geometric calculations, particularly for resin-based materials which may present small surface irregularities produced during molding. This principle is in line with ASTM D792, which uses the fluid displacement method to determine the density and specific gravity of solid materials.

Conceptually, this procedure is also related to the general framework of ASTM C642, used for evaluating density, absorption, and voids in hardened concrete. However, unlike conventional cement concrete, epoxy-based polymer concrete was not dried at a high oven temperature as is common practice in ASTM C642. This adjustment was made to avoid possible changes in the properties of the polymer matrix due to exposure to temperatures approaching or exceeding the glass-transition temperature (T_g), because in this range polymer materials can transition from a rigid state to a softer state (ACI 548.1R). Therefore, the initial dry condition in this study was achieved by conditioning at controlled room temperature until the specimen mass stabilized.

Testing was carried out on 50 × 50 × 50 mm cube specimens after passing through curing and conditioning processes. The specimens were first conditioned at room temperature until reaching thermal equilibrium and free from surface moisture, then weighed to obtain the dry mass in air. Subsequently, the specimens were weighed while suspended in water to obtain the apparent mass in the fluid. The difference between these two measurements represents the volume of water displaced by the specimen, so the specific gravity can be calculated using the hydrostatic equation. In this study, this parameter is used as a quantitative indicator to assess the effectiveness of initial compaction in increasing the internal density of polymer concrete.

The mathematical equation used to calculate the apparent specific gravity is:

$$D_{app} = \frac{W_d}{W_d - W_w} \times \rho_{air}$$

Where:

D_{app} = Apparent Specific Gravity (g/cm³)
W_d = Dry Weight of Specimen (gram)
W_w = Weight of Specimen Submerged in Water (gram)
ρ_{air} = Specific Gravity of Water (g/cm³)

Compressive Strength Testing

Figure 7. Measurement Process (Left) and Compressive Strength Testing (Right)

Compressive strength testing of cube specimens was carried out with reference to ASTM C579 Method B, used for polymer concrete with aggregate sizes 1.6–10 mm and 50 mm cube specimens. Before testing, each specimen that had passed the curing and conditioning stages had its actual dimensions measured using a caliper to obtain a representative compressive cross-sectional area. The specimen was then placed centrally on the bottom plate of the compression testing machine to minimize load eccentricity and the potential for secondary moments. Uniaxial compressive load was then applied continuously and without shock until the specimen reached failure, according to the loading procedure specified in ASTM C579.

RESULTS AND DISCUSSION

Compressive Strength of Concrete

The cube compressive strength results presented in Table 5 indicate that compression casting significantly improved the compressive performance of RCA-based epoxy polymer concrete compared with the non-compacted control group. The mean compressive strength increased from 33.754 ± 1.503 MPa in Cu.N (±0.00 MPa) to 57.426 ± 3.129 MPa in Cu.L (±3.60 MPa) and reached the highest numerical value of 60.190 ± 4.957 MPa in Cu.M (±4.80 MPa), before decreasing to 54.009 ± 11.287 MPa in Cu.H (±6.00 MPa). The corresponding coefficients of variation were 4.45%, 5.45%, 8.24%, and 20.90%, respectively. These values show that all compacted groups had higher mean compressive strength than the control group, but the highest compression level produced the largest data dispersion. Although Grubbs' test at a 5% significance level did not identify any value as an outlier, the relatively high CV% in Cu.H indicates that the response at ±6.00 MPa was less reproducible than the lower compaction levels. Therefore, the lower mean strength at ±6.00 MPa should be interpreted as a numerical tendency rather than a statistically conclusive strength reduction.

Table 5. Recapitulation of Compressive Strength Test Results of Polymer Concrete

RUN[a]	Compression (MPa)	Dimensions (cm)			*A* (cm²)	Compressive Strength (MPa)	Mean (MPa)	SD[b] (MPa)	CV[c] (%)
		p	*l*	*t*					
Cu.N1	± 0.00	5.40	4.97	5.00	26.84	32.04	33.75	1.50	4.45
Cu.N2	± 0.00	5.02	5.39	5.07	27.06	34.37			
Cu.N3	± 0.00	5.37	5.13	4.98	27.55	34.85			
Cu.L1	± 3.60	5.43	5.13	4.97	27.86	61.03	57.42	3.13	5.45
Cu.L2	± 3.60	5.12	5.56	4.93	28.47	55.85			
Cu.L3	± 3.60	4.86	5.46	5.05	26.54	55.40			
Cu.M1	± 4.80	4.95	5.45	5.15	26.98	61.16	60.19	4.96	8.24
Cu.M2	± 4.80	5.49	5.02	4.84	27.56	64.59			
Cu.M3	± 4.80	5.15	5.49	4.99	28.27	54.82			
Cu.H1	± 6.00	4.98	5.60	5.27	27.89	49.13	54.01	11.29	20.90
Cu.H2	± 6.00	5.00	5.35	5.09	26.75	66.92			
Cu.H3	± 6.00	5.13	5.68	4.89	29.14	45.99			

[a] Each specimen group was subjected to Grubbs' test for outlier detection
[b] Standard Deviation
[c] Coefficient of Variation

Table 6. One-way ANOVA for cube compressive strength at different compaction levels

Source of variation	Sum of squares	*df*	Mean square	*F*	*p*-value
Between groups	1295.422	3	431.807	10.531	0.0038
Within groups	328.036	8	41.005		
Total	1623.459	11			

The one-way ANOVA in Table 6 confirmed that compaction level had a significant effect on compressive strength (F (3,8) = 10.531; p = 0.0038). Tukey's HSD post-hoc test in Table 7 showed that all compacted groups were significantly stronger than the non-compacted control group, with adjusted p-values of 0.0083, 0.0043, and 0.0197 for Cu.L, Cu.M, and Cu.H against Cu.N, respectively. However, no statistically significant differences were observed among the compacted groups themselves (p > 0.05). This indicates that compression casting significantly improves compressive strength relative to the non-compacted condition, but the differences among ±3.60 MPa, ±4.80 MPa, and ±6.00 MPa are not statistically conclusive under the present sample size.

Table 7. Tukey HSD pairwise comparison for cube compressive strength

Comparison	Mean difference (MPa)	p-adjusted	Significance
Cu.L *vs* Cu.N	23.673	0.0083	Significant
Cu.M *vs* Cu.N	26.437	0.0043	Significant
Cu.H *vs* Cu.N	20.260	0.0197	Significant
Cu.M *vs* Cu.L	2.763	0.9497	Not significant
Cu.H *vs* Cu.L	-3.413	0.9116	Not significant
Cu.H *vs* Cu.M	-6.177	0.6541	Not significant

Visually, the boxplot in Figure 8 shows that compaction pressures up to 4.80 MPa not only increased the mean values but also maintained a relatively controlled data distribution. In contrast, at the 6.00 MPa level, the data range became wider, indicating increased variability in specimen responses. This pattern suggests that the effect of initial compaction on compressive strength is not entirely linear; there is an optimum compaction level, which in this study was in the range of 4.80 MPa. Compared to the 3.60 MPa level, the average increase at 4.80 MPa was still 4.81%, but when the pressure was raised to 6.00 MPa, the average actually decreased by approximately 10.27% relative to the medium level. These findings indicate that initial compaction is indeed effective in improving compressive performance, but excessively high pressure does not always yield a commensurate increase in strength

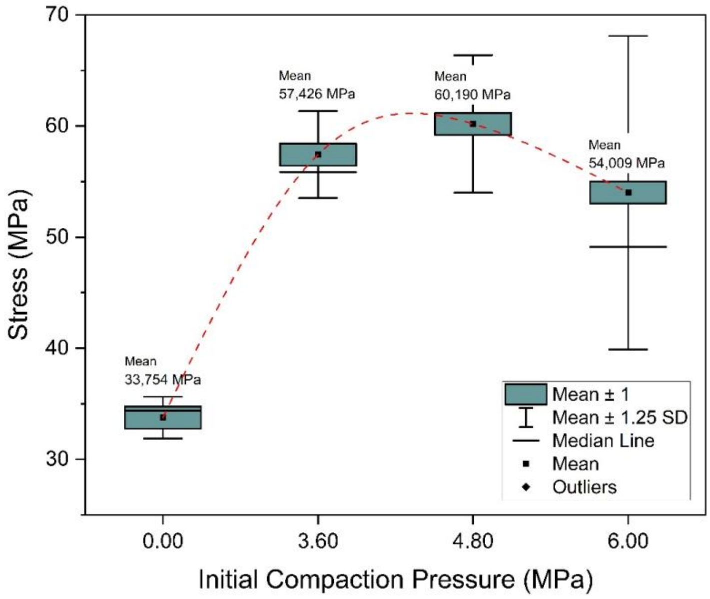

Figure 8. Compressive Strength Test Results

From material mechanisms, the pronounced increase of compressive strength in the low to intermediate range of compaction levels could be demonstrated by virtue of mixture densification, reduction of confined air and strengthening of inter-particle contact providing more efficient stress transfer paths within the matrix. Previous research on fresh concrete compression and compression casting suggests that applying pressure over the fresh mixture could increase material compressive strength through porosity reduction and increased density (Nematzadeh & Naghipour, 2012a; Hameed *et al.*, 2023; Nemati *et al.*, 2023). In the context of polymer concrete, the quality of packing and microstructural homogeneity is also known to be very decisive for mechanical performance, because internal voids and non-uniform binder distribution can act as weak points that accelerate stress concentration and damage initiation (Palamarchuk *et al.*, 2024; Salami *et al.*, 2024).

Although the ±6.00 MPa level produced the highest specific gravity and the lowest water absorption, it did not generate the highest mean compressive strength. This indicates that physical densification and compressive load-bearing capacity are not governed by exactly the same mechanism. Specific gravity primarily reflects bulk density (ASTM C642), while water absorption represents the reduction of connected water-accessible voids (ASTM C413). In contrast, compressive strength is more sensitive to the continuity of load-transfer paths, resin distribution, aggregate–matrix bonding, and local defect formation within the specimen (Haidar *et al.*, 2011; Ferdous *et al.*, 2020). Therefore, the lower mean compressive strength at ±6.00 MPa should be interpreted cautiously as a numerical tendency rather than a statistically conclusive reduction. Under excessive compression, the semi-dry mixture may experience local non-uniformity, uneven resin redistribution, disturbance of the aggregate–filler skeleton, or densification heterogeneity between specimens (Liu *et al.*, 2022; Hameed *et al.*, 2023). These mechanisms can disrupt mechanical efficiency even when bulk physical densification increases. Thus, compression casting is effective in improving the compressive strength of RCA-based epoxy polymer concrete compared with the non-compacted condition, but its effectiveness depends strongly on selecting an appropriate pressure level.

Absorption Value

The absorption test results in Table 8 show that increasing the compression casting level was followed by a very significant decrease in water absorption. The mean absorption decreased from 1.563% in the group without compaction (Cu.N) to 0.387% at the 3.60 MPa level (Cu.L), 0.233% at the 4.80 MPa level (Cu.M), and 0.216% at the 6.00 MPa level (Cu.H). Thus, compared to the control specimens, the reduction in absorption reached approximately 75.2%, 85.1%, and 86.2%, respectively. In general, this finding indicates that initial compaction effectively suppresses the material's ability to absorb water, which, in the context of ASTM C413, is more appropriately understood as a reduction in accessible water paths within the material, not as a direct measure of permeability. ASTM C413 itself states that this test is used to determine absorption in polymer concrete and that the results are not a permeability test.

Table 8. Absorption Test Results of Polymer Concrete

RUN	Compression (MPa)	Dry Mass (gram)	Saturated Mass[c] (gram)	Absorption (%)	Mean (%)	SD[a] (%)	CV[b] (%)
Cu.N1	± 0.00	284.40	289.00	1.62	1.563	0.398	25.46
Cu.N2	± 0.00	289.70	293.00	1.14			
Cu.N3	± 0.00	275.20	280.51	1.93			
Cu.L1	± 3.60	307.30	308.50	0.39	0.387	0.065	16.83
Cu.L2	± 3.60	312.90	313.90	0.32			
Cu.L3	± 3.60	293.50	294.83	0.45			
Cu.M1	± 4.80	308.10	308.79	0.22	0.233	0.032	13.78
Cu.M2	± 4.80	300.10	300.90	0.27			
Cu.M3	± 4.80	317.70	318.36	0.21			
Cu.H1	± 6.00	324.00	324.65	0.20	0.216	0.023	10.83
Cu.H2	± 6.00	300.30	300.91	0.20			
Cu.H3	± 6.00	307.00	307.75	0.24			

[a] Standard Deviation
[b] Coefficient of Variation
[c] The test specimens underwent the boiling process

The decreasing pattern of absorption values presented in Figure 9 is a form of diminishing marginal return. The largest drop was with the transition to the Cu. N to Cu. These early decreases turned from sharp in the L condition, 1.563%→0.387%, to more gradual at the Cu. M and Cu. H levels. This suggests that nearly all of the open space and air pockets were likely eliminated early during compaction leaving only marginal increases in structural integrity for any subsequent pressure applied to the other voids left remaining. This outcome of CCT is consistent with the findings of Hameed *et al.*, (2022), who found that application of compression casting technique positively affects water absorption properties of concrete composed solely from recycled aggregates and there is a tendency for decreasing water absorption due to increasing compaction pressures.

While the mechanistic reasons behind these results are attributed to more mixture densification caused by the pressure in the fresh phase, which improves inter-particle contact and shrinks the volume of interconnected voids around particles. This interpretation is relevant for mixtures using RCA, as recycled aggregates generally have higher absorption and porosity due to the old mortar attached to their surface. A recent review on RCA also affirms that the presence of adhered mortar increases water absorption and decreases the quality consistency of recycled materials (Muhammad *et al.*, 2024). Therefore, the very sharp decrease in absorption in this study can be seen as an indication that compression casting successfully compensated for some of RCA's inherent weaknesses by producing a denser and more homogeneous polymer concrete microstructure.

Specific Gravity

The specific gravity test results in Table 9 show a consistent trend, namely that increasing the compression casting level is followed by an increase in the specific gravity of the RCA-based polymer concrete. The mean specific gravity increased from 2.162 g/cm^3 in the group without compaction (Cu.N) to 2.248 g/cm^3 at the 3.60 MPa level (Cu.L), 2.272 g/cm^3 at the 4.80 MPa level (Cu.M), and 2.309 g/cm^3 at the 6.00 MPa level (Cu.H). Compared to the control specimens, these increases were equivalent to approximately 4.0%, 5.1%, and 6.8%, respectively. This pattern confirms that initial compaction can increase mixture densification, so that the volume of trapped voids is reduced and the particle arrangement becomes denser.

Table 9. Recapitulation of Specific Gravity Test Results of Polymer Concrete

RUN	Compression (MPa)	Specific Gravity (g/cm³)	Volume (cm³)
Cu.N1	± 0.00	2.200	129.30
Cu.N2	± 0.00	2.081	139.20
Cu.N3	± 0.00	2.204	124.85
Cu.L1	± 3.60	2.220	138.42
Cu.L2	± 3.60	2.254	138.82
Cu.L3	± 3.60	2.270	129.32
Cu.M1	± 4.80	2.282	135.01
Cu.M2	± 4.80	2.280	131.60
Cu.M3	± 4.80	2.255	140.89
Cu.H1	± 6.00	2.349	137.94
Cu.H2	± 6.00	2.286	131.36
Cu.H3	± 6.00	2.291	134.02

The relationship between specific gravity and water absorption, as presented in Figure 9, confirms that compression casting improved the physical densification of the RCA-based epoxy polymer concrete. Specimens with higher specific gravity generally exhibited lower water absorption, indicating that the increase in bulk density was accompanied by a reduction in connected water-accessible voids. This trend is consistent with the role of fresh-state compaction in improving particle packing, reducing entrapped air, and producing a more compact aggregate–filler–resin structure (Haidar *et al.*, 2011; Salami *et al.*, 2024). Compared with the non-compacted group, the compacted specimens also showed a more controlled distribution of specific gravity, particularly at the low and medium pressure levels. This suggests that compression casting not only increased material density but also improved the uniformity of the internal structure. However, the interpretation of specific gravity should remain limited to physical densification, because higher density does not necessarily guarantee proportional improvement in compressive strength.

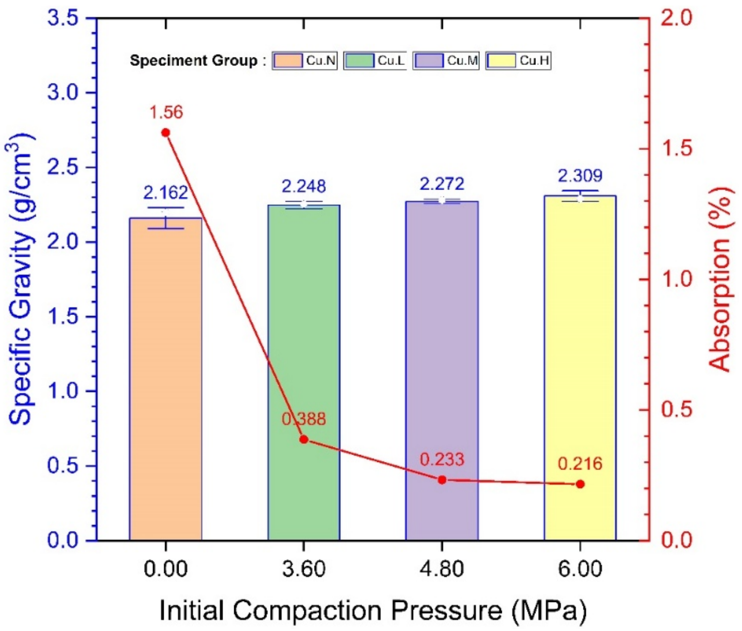

Figure 9. Specific Gravity and Absorption Test Results

Discussion

This study reveals that compression casting substantially enhances the mechanical and physical performance of epoxy polymer concrete based on recycled coarse aggregate (RCA). Results and discussion: The key findings indicate that the extent of the initial compaction is correlated with an increase in compressive strength as well as a decrease in absorption and an increase in material specific gravity. This suggests that the densification process plays a fundamental role in governing the final performance of polymer concrete.

Compressive Strength Mechanism

The increase in compressive strength at low to intermediate compaction levels (±3.60 MPa to ±4.80 MPa) indicates that compression casting improved the internal consolidation of RCA-based epoxy polymer concrete. At ±4.80 MPa, the mean compressive strength increased by 78.32% compared with the non-compacted control group. This improvement can be attributed to higher packing density, reduced entrapped air, and stronger inter-particle contact, which collectively enhance stress transfer within the resin–aggregate–filler system.

The mechanism is also supported by Kępniak *et al.*, (2024), who reported that recycled aggregate in polymer concrete may develop an interfacial coating layer formed by resin and fine particles. Such a coating layer can improve the continuity of the aggregate–matrix transition zone and partially compensate for the porous and heterogeneous nature of RCA. In the present study, epoxy resin and Type C fly ash may have contributed to a similar effect by coating RCA particles, filling surface pores, and improving the internal connectivity of the composite.

Void reduction is particularly important in polymer concrete because internal pores and discontinuities can act as local stress concentrators and initiate premature failure. A denser internal structure allows load to be transmitted more uniformly through the aggregate skeleton and polymer matrix, thereby increasing compressive resistance. Thus, the strength improvement at ±3.60 MPa and ±4.80 MPa can be interpreted as the combined effect of better densification, improved aggregate–matrix interaction, and more continuous load-transfer paths.

However, the pressure–strength relationship was not fully linear. At ±6.00 MPa, the mean compressive strength was numerically lower than that at ±4.80 MPa, although the difference among compacted groups was not statistically significant. The higher dispersion at ±6.00 MPa suggests that excessive pressure may induce non-uniform resin redistribution, local densification heterogeneity, or uneven stress transmission in the semi-dry polymer concrete mixture. Therefore, while compression casting is effective in improving compressive strength, the applied pressure must be properly controlled to achieve a more reproducible mechanical response.

Physical–Mechanical Divergence at High Compaction Pressure

The divergent response observed at the highest compaction level indicates that improved physical densification does not necessarily lead to a proportional increase in compressive strength. In general, compression casting reduces entrapped air, improves particle packing, and enhances contact among aggregates, fillers, and the resin matrix, thereby promoting higher specific gravity and lower water absorption (Nematzadeh & Naghipour, 2012a, 2012b; Hameed *et al.*, 2023; Nemati *et al.*, 2023). However, these two physical indicators mainly reflect bulk density and the reduction of connected water-accessible voids, whereas compressive strength is more strongly governed by the continuity and homogeneity of the internal load-transfer network.

This distinction is particularly important in epoxy polymer concrete, where mechanical performance is highly sensitive to resin continuity, aggregate packing, aggregate–matrix bonding, and local defect distribution (Haidar *et al.*, 2011; Ferdous *et al.*, 2020; Palamarchuk *et al.*, 2024). At moderate compaction levels, the reduction of voids and the improvement of inter-particle contact are beneficial for both physical and mechanical performance. In RCA-based polymer concrete, this effect may be further supported by resin and fine-particle coating around recycled aggregate surfaces, which can improve the transition zone and partially compensate for the porous nature of RCA (Kępniak *et al.*, 2024). Nevertheless, when the applied pressure becomes excessive, the semi-dry mixture may no longer deform uniformly. Local resin migration, resin-rich or resin-deficient zones, disturbance of the aggregate skeleton, and uneven stress transmission may develop, even though the overall specimen becomes denser.

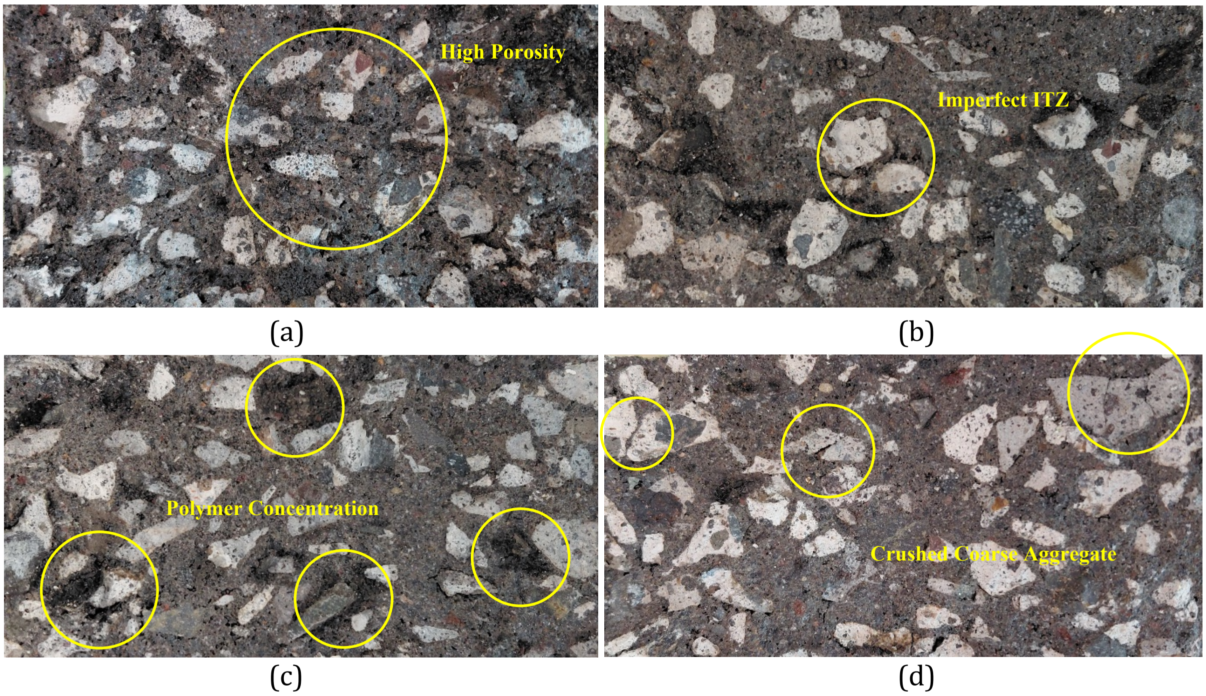

Figure 10. Split-section morphology of compressed RCA–epoxy polymer concrete
(a) Compression Level ±0.00 MPa; Abundant internal voids
(b) Compression Level ±3.60 MPa; Reduced voids with imperfect ITZ and local polymer concentration
(c) Compression Level ±4.80 MPa; Denser matrix with fewer voids, improved ITZ, and local polymer concentration
(d) Compression Level ±6.00 MPa; highly compacted structure with crushed recycled coarse aggregate.

The visual observations in Figure 10 support this interpretation. The split sections of the specimens compacted at ±0.00 MPa still show a considerable number of internal voids, indicating that the mixture remained relatively loose and discontinuous. At ±3.60 MPa and ±4.80 MPa, the number of visible voids is clearly reduced, indicating more effective densification; however, some localized polymer-matrix concentration can also be observed. At the highest pressure level of ±6.00 MPa, most visible voids were substantially reduced, but several recycled coarse aggregate particles appeared fractured or locally damaged. This visual evidence suggests that, although high pressure improved bulk compactness, it may also have introduced localized damage within the RCA phase or the surrounding old mortar layer

Such localized damage is relevant because RCA commonly contains adhered old mortar, pores, and possible microcracks, which make it more vulnerable to stress concentration under high compression. These defects may not be captured directly by water absorption or specific gravity measurements, since those tests primarily represent bulk physical characteristics. Under compressive loading, however, fractured RCA particles, damaged old mortar zones, or local interfacial disruption can act as weak points for crack initiation and progressive failure. Therefore, the lower mean compressive strength at ±6.00 MPa, despite the higher specific gravity and lower absorption, can be interpreted as the result of competition between beneficial physical densification and detrimental local heterogeneity or aggregate damage.

The statistical behavior of the data is consistent with this interpretation. The ±6.00 MPa group exhibited the largest compressive strength dispersion, indicating lower mechanical reproducibility at the highest pressure level. Although no specimen was identified as an outlier and the differences among compacted groups were not statistically significant, the greater variability suggests that excessive pressure may generate less uniform internal structures in semi-dry RCA-based epoxy polymer concrete. Accordingly, within the tested range, ±4.80 MPa produced the highest mean compressive strength, whereas ±6.00 MPa was more effective in improving physical densification but less consistent in sustaining mechanical performance. The proposed interpretation of the pressure-dependent response is conceptually summarized in Figure 11 and visually supported by the fractured-section observations in Figure 10.

Physical Densification Mechanism

The reduction in water absorption and the increase in specific gravity indicate that compression casting improved the physical compactness of RCA-based epoxy polymer concrete. Water absorption mainly reflects connected water-accessible voids, whereas specific gravity represents the bulk density of the hardened composite. The sharp decrease in absorption from the non-compacted group to the low compaction level suggests that a substantial portion of open voids and entrapped air was reduced during the early stage of compression. Similar mechanisms have been reported in fresh concrete compression and compression casting studies, where pressure application improves particle packing, reduces pore volume, and increases material density (Nematzadeh & Naghipour, 2012b, 2012a; Hameed *et al.*, 2023; Nemati *et al.*, 2023).

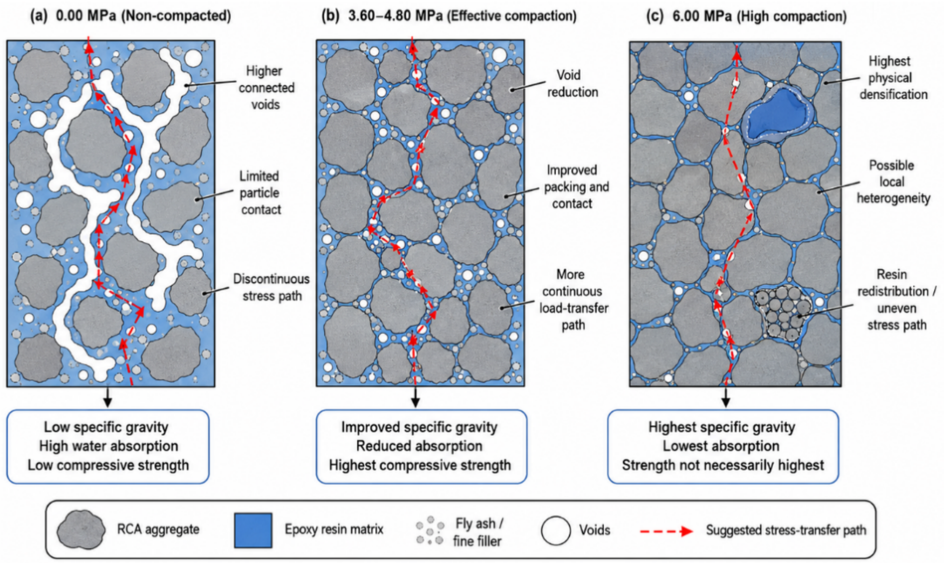

Figure 11. Conceptual Mechanism of Compression Casting

The subsequent reduction in absorption became more gradual as pressure increased, indicating a diminishing marginal effect after the major connected voids had been reduced. At the same time, the increase in specific gravity suggests that the aggregate–filler–resin system became more compact through better particle rearrangement and filling of intergranular spaces. This mechanism is particularly relevant for RCA-based mixtures because RCA commonly contains adhered old mortar and internal pores that increase absorption and reduce material uniformity (McNeil & Kang, 2013; Muhammad *et al.*, 2024). Fly ash may also contribute as a fine filler by improving particle packing and modifying the resin–filler structure (Rochman *et al.*, 2023; Rochman *et al.*, 2023).

Therefore, the simultaneous decrease in water absorption and increase in specific gravity confirms that compression casting enhanced the physical densification of the material. However, these physical indicators should not be interpreted as direct predictors of compressive strength, since strength is also governed by resin continuity, aggregate–matrix bonding, aggregate skeleton stability, and local defect distribution (Haidar *et al.*, 2011; Ferdous *et al.*, 2020; Palamarchuk, Yudaev & Chistyakov, 2024).

Integrated Implications and Limitations

The findings indicate that compression casting is an effective processing strategy for improving the performance of epoxy polymer concrete incorporating 100% RCA and Type C fly ash. Within the tested range, the intermediate pressure level of ±4.80 MPa produced the highest mean compressive strength, whereas the highest pressure level of ±6.00 MPa produced the highest specific gravity and the lowest water absorption. As conceptually summarized in Figure

10, the optimum compression pressure may differ depending on whether the target performance is compressive strength or physical densification. For strength-oriented applications, excessive pressure should be avoided because it may increase local heterogeneity and reduce mechanical reproducibility. For applications prioritizing low absorption and high density, higher pressure may still be beneficial, provided that the uniformity of the resin–aggregate–filler system can be controlled.

From a practical perspective, the results suggest that compression casting can improve the quality of RCA-based epoxy polymer concrete for precast, repair, and non-reinforced components requiring high density, low absorption, and improved compressive performance. The use of RCA also supports sustainable material development by providing a higher-value pathway for construction and demolition waste utilization. However, the findings should be interpreted within the scope of a process-focused experimental design. The non-compressed RCA-based epoxy polymer concrete was used as the internal control, while additional reference mixtures, such as epoxy polymer concrete with natural coarse aggregate or OPC-based concrete with RCA, were not included. Therefore, the present results cannot independently quantify the isolated effect of RCA substitution or directly compare polymer-based and cement-based RCA systems.

Several limitations should also be acknowledged. First, the compaction pressure range was limited to four levels, so other possible optimum pressures between ±4.80 MPa and ±6.00 MPa have not been fully identified. Second, the proposed mechanism was inferred from macroscopic indicators, namely compressive strength, water absorption, and specific gravity, without direct microstructural validation using SEM, X-ray CT, or porosity analysis. Third, this study focused on short-term physical and compressive performance; therefore, flexural behavior, chemical resistance, creep, fatigue, and long-term durability remain to be investigated. Future studies should incorporate reference mixtures, larger sample sizes, microstructural characterization, and durability testing to verify the broader applicability of compression casting for RCA-based epoxy polymer concrete.

CONCLUSION

This study demonstrates that compression casting improves the mechanical and physical performance of epoxy polymer concrete incorporating 100% recycled coarse aggregate (RCA) and Type C fly ash. Compared with the non-compacted control group, the mean compressive strength increased by 70.13% at ±3.60 MPa and reached the highest numerical increase of 78.32% at ±4.80 MPa. At ±6.00 MPa, the strength remained higher than the control group, with an increase of 60.01%, but showed greater variability. Therefore, ±4.80 MPa can be regarded as the best-performing pressure for compressive strength within the tested range, although it should not be interpreted as a statistically definitive optimum because the differences among the compacted groups were not significant under the present sample size.

The physical properties improved continuously with increasing compaction pressure. Specific gravity increased by 4.0%, 5.1%, and 6.8%, while water absorption decreased by 75.2%, 85.1%, and 86.2% at ±3.60 MPa, ±4.80 MPa, and ±6.00 MPa, respectively. These results indicate that compression casting enhanced physical densification, reduced connected water-accessible voids, and improved the compactness of the aggregate–filler–resin system. However, the different trends between compressive strength and physical properties show that higher bulk densification does not necessarily lead to proportional mechanical improvement. Overall, compression casting is a promising processing strategy for improving RCA-based epoxy polymer concrete when the applied pressure is properly controlled. Further studies with larger sample sizes, additional reference mixtures, and microstructural characterization are needed to confirm the optimum pressure range and clarify the mechanisms governing the physical–mechanical response of compressed RCA-based epoxy polymer concrete.

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AUTHOR CONTRIBUTION STATEMENT

Khusnul Aldi Saputra contributed as the primary author and principal researcher, including conceptualizing and designing the study, conducting the laboratory experiments, analyzing the results, and preparing the original manuscript draft. Eva Arifi contributed to the supervision of the research design and manuscript development, provided guidance during the laboratory work, and assisted in language editing and manuscript refinement. Desy Setyowulan contributed to the supervision of the research design and manuscript preparation, provided guidance in data analysis and data presentation, and supported the critical review of the manuscript. All authors have read and agreed to the published version of the manuscript

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