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Research Article

Clustering analysis of compressive strength of structural recycled aggregate concrete

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ABSTRACT

Clustering analysis primarily highlights the inhomogeneity of data and can be utilized in structural engineering to demonstrate strength irregularity. It is well-known that strength irregularity between neighboring floors within a structure or among structural elements can lead to non-holistic behavior. Therefore, the clustering of compressive strength holds significant importance. Despite the relevance, only a few studies have addressed the clustering of compressive strength in recycled aggregate concrete (RAC) and proposed potential solutions for clustering issues. This paper aims to investigate the clustering of compressive strength in RAC and explore viable solutions. In this experimental study, four concrete groups were produced under standard conditions. The first group included natural aggregate concretes (NAC) designed with the Absolute Volume Method (AVM) as control concretes. The second group, comprised of RAC, was designed with the equivalent mortar volume method (EVM) as the control RAC. The third group consisted of RAC treated with silica fume (SF) and designed using AVM, while the fourth group included RAC designed with EVM. Statistical analyses were conducted on the 28-day compressive strength test results. The results indicated that the strength class of compressive strength clusters varied among the four groups. The clustering of test results was influenced by the type of concrete components used and the design method employed. Additionally, using silica fume and adopting the Absolute Volume Method reduced strength fluctuation and regulated the strength class of clusters by bringing them closer together. In contrast, the Equivalent Mortar Volume Method resulted in a greater dispersion of strength classes. The clustering effect of recycled aggregate (RA) was more pronounced than that of natural aggregate (NA). Given these findings, it is essential to implement measures when utilizing RAC in sustainable structures to address potential clustering issues.

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1. INTRODUCTION

Evaluation of experimental results is a crucial aspect of engineering structures, with guidelines for evaluation typically well-defined in relevant codes and regulations [1–4]. Material quality control is essential for structural integrity, particularly for large structures such as dams, reinforced concrete buildings, and airport aprons. Quality control must be conducted for each unit of concrete production, as mandated by codes, and it is imperative to evaluate all data for each structural unit statistically. This approach, required by standards such as TS EN 206-1, minimizes human er-

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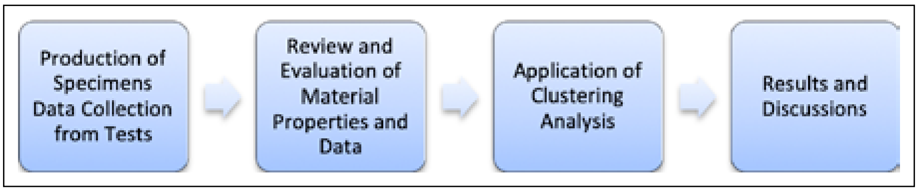

Figure 1. Flowchart of the study.

rors and enhances societal safety. The statistical evaluation of concrete compressive strength is a well-documented subject in the literature [5–8], with many studies employing main statistical parameters (mean, standard deviation, etc.) and distribution functions [6, 7, 9]. The normal distribution function is commonly used and deemed suitable for assessing concrete compressive strength [6, 7, 10, 11]. Typically, statistical evaluations are based on compressive strength test data, observing population behavior through fitting distribution functions. However, clustering within test results can also occur, even when population properties are consistent across groups. Therefore, it is essential to evaluate both the overall data properties and the cluster-specific properties within the big data set.

Clustering analysis is a statistical method that highlights data inhomogeneity and can be a valuable tool in structural engineering for assessing strength irregularity in experimental data. Strength irregularity between neighboring floors or structural elements can lead to non-holistic behavior, affecting soft-story irregularity in concrete structures controlled by national codes. Consequently, the clustering of compressive strength impacts both material and structural behavior, making it a critical area of study. While research on the clustering of experimental results in conventional concrete (NAC) exists [12], this subject has not been extensively studied for recycled aggregate concrete (RAC). For instance, Kılınçarslan et al. [12] investigated the clustering of strengths in concrete with various aggregate types, finding different clustering behaviors across aggregate types, with compressive strengths ranging from 40 to 55 MPa and specific mean strengths for each cluster. The findings highlighted the relationship between aggregate mechanical strength and the clustering behavior of concrete properties. In structural engineering, all concrete or reinforced concrete structure elements are desired to exhibit uniform strength classes. Structural element strength variation can lead to inadequate load-bearing capacity and issues such as soft floors, adversely affecting structural performance under lateral loads like earthquakes. Therefore, it is essential to consider clustering in compressive strength data alongside comprehensive statistical analysis when constructing buildings with concrete of the same strength class. The reuse and recycling of materials, including RAC, are encouraged within the sustainability concept. However, proper clustering analysis is necessary to address potential soft floor issues due to strength fluctuation in RAC structures, and possible solutions must be evaluated. Sustainable buildings incorporating RAC are gaining attention, with green buildings expected to become more prevalent globally.

Table 1. Properties of binders

Contents	SF	Cement
Fe_2O_3 (%)	1.66	3.4
Al_2O_3 (%)	0.72	4.8
SiO_2 (%)	91.42	18.9
SO_3 (%)	0.37	3.42
CaO (%)	0.52	64.7
K_2O (%)	1.21	0.4
MgO (%)	0.92	1.4
Na_2O (%)	0.38	0.7
Density (g/cm^3)	0.642	3.11
Loss on ignition (%)	1.72	1.82
Chlorine ratio (%)	0.04	0.0241
Activity index (%)	118	–
Specific surface area (m^2/kg)	21290	3840

SF: Silica fume.

This paper aims to investigate RAC behavior and the implications of its use. Few studies have focused on the clustering of concrete compressive strength and potential clustering problems. Clustering compressive strength data in concrete with various components can result in soft floors and fluctuating strength distribution in reinforced concrete structures. Typically, concrete structures are assumed to have uniform properties, but research indicates that various factors influence compressive strength and clustering. This study investigated clustering in RAC and potential solutions, producing four concrete groups under standard laboratory conditions. Each group consisted of 30 specimens, cured in water at standard temperature and subjected to compressive strength testing at 28 days, yielding 120 test results. Statistical analyses were performed on the data.

2. MATERIALS AND METHODS

This paper employed different concrete components and mixing methods to support the paper's hypothesis. The general methodological flow of the study is given in Figure 1. The production of the specimens and data collection from the conducted compressive strength tests was the first stage of the study. Materials were prepared to mix, and workability regulations of the concretes were made. Then, the tests were conducted. The data collected from the experiments were reviewed and evaluated. In this stage, the data were corrected and assessed using the literature. This stage can be named as validation part of this paper. Then,

Table 2. Aggregate types and their properties

Notation	Size, mm	LA abrasion value, %	Residual content, %	Density, g/cm^3	Water absorption, %
Sand	0–4	–	–	2.81	1.31
NA	11.2–22.4	24	–	2.70	0.75
	4–11.2	–	–	2.73	0.72
RA	11.2–22.4	55	52.5	2.00	8.95
	4–11.2	–	39.2	2.06	8.80

RA: Recycled aggregate; NA: Natural aggregate; LA abrasion: Los Angeles abrasion test.

the data was used in clustering analysis, and the clusters of the compressive strengths of four concrete groups were obtained. In the last stage of the paper, the results were figured out, presented, and discussed.

2.1. Materials

CEM I 42.5R cement, which conforms to the specifications of TS EN 197-1 (2012), was utilized in the mixtures for general purposes. The characteristics of the binders employed in this study, including silica fume (SF) and cement, are presented in Table 1. CEM I cement was selected primarily due to its widespread usage and high regional prevalence. Consequently, a commonly utilized cement was chosen over a material with more specific applications.

The concrete mixes employed two coarse aggregates: natural gravel and recycled coarse aggregate. The granulometry of the aggregates remained unchanged and was consistent across all concrete mixtures. Calcareous natural aggregate and sand were used in the fresh mixes, as detailed in Table 2. A superplasticizer (SP) with a polycarboxylate ether base was incorporated to enhance the flowability of the concretes, thereby improving low workability, as outlined in Table 3. The S2 slump class, by TS EN 206-1 (2002), was utilized for all mixes to facilitate ease of production and mold placement. It is well-known that plasticizers reduce the pore content in fresh concrete, resulting in a more compact medium. The recycled aggregate originated from concrete waste, precisely elements of reinforced concrete structures. The compressive strength of the recycled aggregate source was less than 20 MPa, classifying it as low strength.

2.2. Concrete Design Method, Mixing, Curation and Testing

In the laboratory, fresh concrete mixes were prepared using a constant cement dosage and water-to-binder ratio, aiming for a target strength of C30/37 (Table 4). The mixing methods employed were the Equivalent Mortar Volume Method (EVM) and the Absolute Volume Method (AVM) by TS 802 (Table 5). The AVM is a widely adopted method recognized in concrete standards such as TS 802, ACI 211, and IS 10262. Additionally, the EVM, a mix design procedure proposed in the literature on recycled aggregate concrete, has demonstrated satisfactory results. Therefore, this study compares these methods and examines their performance.

Table 3. The properties of SP

Content	SP
Structure of material	Polycarboxylic ether
Alkaline ratio (%)	<3
Chlorine ratio (%)	<0.1
Density (kg/l)	1.08–1.14
Color	Amber

SP: Superplasticizer.

Table 4. Components of concrete series

Components	NAC	RAC	RAC.SF	RAC.EVM
Water, kg/m^3	163	163	163	123
Cement, kg/m^3	340	340	323	255
SP, %	0.75	0.85	0.95	1.55
SF, kg/m^3	–	–	17	–
Sand, kg/m^3	806	806	806	608
NA (11–22.4 mm), kg/m^3	775	–	–	–
NA (4–11.2 mm), kg/m^3	392	–	–	–
RA (11–22.4 mm), kg/m^3	–	574	574	774
RA (4–11.2) mm), kg/m^3	–	296	296	368

NAC: Natural aggregate concrete; RAC: Recycled aggregate concrete; SF: Silica fume; EVM: Equivalent mortar volume.

Table 5. Compressive strength results in concrete

Components	RAC.EVM	RAC	RAC.SF	NAC
Average compressive strength	51.89	39.20	42.44	44.12
Std. deviation of compressive strength	3.95	2.52	1.49	2.63
Minimum compressive strength	45.55	28.37	34.48	36.55

NAC: Natural aggregate concrete; RAC: Recycled aggregate concrete; SF: Silica fume; EVM: Equivalent mortar volume.

The AVM requires that a unit volume of concrete includes concrete components in specific proportions for each strength class, as described in Equation 1. The primary components of concrete are cement, water, and aggregate, among others [13].

$$V_1 m^3 = V_{agg} + V_{cem} + V_w + V_{ch} + V_{air} \quad (1)$$

Here, V_{ch} is the volume of chemicals, V_{cem} is the volume of cement, V_{agg} is the volume of aggregate, V_w is the volume of water, and V_{air} is the volume of air in concrete.

In the Absolute Volume Method (AVM), as defined by TS 802, the initial step involves determining the quantity of binding materials. During this stage, parameters such as water and water-to-binder ratios are established. Typically, the material content that occupies one cubic meter of volume is calculated as the unit volume of concrete. Subsequently, the determined material volumes (e.g., cement, water) are subtracted through a reverse calculation process from the unit volume (1 m^3).

Conversely, the Equivalent Mortar Volume Method (EVM) requires that recycled aggregate concrete (RAC) and natural aggregate concrete (NAC) maintain a specific proportion of total mortar volume to natural gravel. The objective is to achieve a consistent aggregate volume in the mixture for both RAC and NAC. The amount of mortar present in recycled aggregate (RA) is a critical factor and must be quantified [14, 15] (Table 2). The mortar content in RA is dissolved using a 0.1 M HCl solution, leaving behind coarse natural aggregate. Consequently, the mortar volume is incorporated into the new mortar content of the fresh mixture, and the remaining portion is considered part of the aggregate volume. Thus, a portion of the calculated mortar and aggregate volumes in the mix is supplied by RA, with the remaining volume being added to the mixtures.

EVM required the constant volume of aggregate, and the volume was calculated as (Eq.3) [16]:

$$V_{RCA}^{RCA-concrete} = \frac{V_{NA}^{NAC} \times (1-R)}{(1-RMC) \times \frac{SG_b^{RCA}}{SG_b^{OVA}}} \quad (2)$$

Here, RMC is the residual mortar content of RA, V_{NA}^{NAC} is the volume ratio of fresh NA in control concrete, $V_{RCA}^{RCA\text{-}concrete}$ is the volume ratio of coarse aggregate in RAC, SG_b^{OVA} and SG_b^{RCA} is original virgin aggregate, and the bulk specific gravity of RA, respectively, and R is the volume fraction of fresh NA content of RAC to fresh NA content of control concrete.

Fresh concrete was cast properly and molded (ASTM C192/C192M–13a (2013)). The vibration was also employed to settle the fresh concrete into the molds. 15 cm cube specimens were produced. The total number of specimens for each series was 30, cured in 22∓2 °C water. The curing process was applied to the specimens for 28 days. The concrete specimens (28 days old) were applied to the tests, and a 3000 kN compression machine was used to perform the compressive strength test according to TS EN 12390-3 (2010) (Table 5).

According to TS 500 (Requirements for design and construction of reinforced concrete structures), the compressive strength of concrete was determined by a 90% confidence interval. However, in this research, the opposite of TS 500, a 95% confidence interval, was considered to increase the accuracy. The strength class is NAC, RAC, and RAC.SF and RAC.EVM was found by using Eq. 3-4 (TS EN 206):

$$f_{c,\,avg} \geq f_{ck} + 1.96\,\sigma \quad (3)$$
$$f_{c,\,min} \geq f_{ck} - 4.0 \quad (4)$$

Here, $f_{c,\,min}$, and σ are the min. comp. Strength (MPa) and standard deviation, respectively, $f_{c\,avg}$ and f_{ck} are the mean and characteristic compressive strengths (MPa).

2.3. Evaluation of Test Data by Statistical Methods

This study investigated the natural cluster structure of various concrete types using Hierarchical Cluster Analysis (HCA). The clusters were naturally determined, and their accuracy was verified with k-means clustering. Cluster analysis revealed the topography of the measured data, allowing the identification of possible scatter in the strength waves of the concrete clusters. Consequently, changes in the strength class within the measured data of the clusters can be readily calculated—notably, NAC, RAC, and RAC. SF was naturally divided into two clusters each, while RAC. EMV was split into three clusters. The movement of concrete units between clusters was determined using diagonal dendrograms, and the data structure was examined by visualizing the clustering results with dendrograms, which also illustrated the branches of the clusters. The statistical significance of the relationships between clusters obtained from HCA results was assessed using the Chi-square test, providing an overview of the study data's general characteristics. This approach offers insights into the similarity of concrete components concerning strength classes.

Additionally, a structure called a tanglegram, using mutual dendrograms was discussed and employed as a method of classification and comparison. Therefore, the classification and comparison of the results were performed using tanglegrams. The primary advantage of this system is the cross-examination of movements between concrete units, which form the characteristics of the strength classes. Comparisons with the control indicated the direction in which the strength classes moved across different concrete types. One critical factor influenced by this method was the sample size; increasing the number of samples allows for a more detailed examination of the strength class movements. Clustering methods were applied to concrete groups based on their general structure, while Chi-square analysis was used to measure the statistical significance of these groups. All statistical analyses were conducted using R statistical software [17].

2.3.1. Hierarchical Cluster Analysis

Hierarchical Cluster Analysis (HCA) is a statistical method used to partition data into clusters based on the similarities among data points. The primary objective of cluster analysis is to ensure heterogeneity between clusters and homogeneity within clusters. The cluster analysis results are visualized using dendrograms, illustrating the hierarchical relationships among objects [18]. This study's data set was segmented into clusters using the centroid linkage algorithm and Euclidean distance. The centroid linkage method, one of the algorithms in HCA, relies on the means of observations that form the cluster [19]. In addition to HCA, k-means clustering analysis was performed, and the resulting groupings were consistent with those obtained through HCA. Euclidean distance (d):

$$d_{ij} = \sqrt{\sum_{m=1}^{M} (X_{im} - X_{jm})^2} \quad (5)$$

where the sum is extended over the M variables which characterize each pair of objects i and j. The central concept of the centroid linkage technique is to consider the distance between the centroids of the data points in clusters. The equation for the centroid-based linkage approach is below (Centroid of a finite set of k points x1, x2, x3, …, xn).

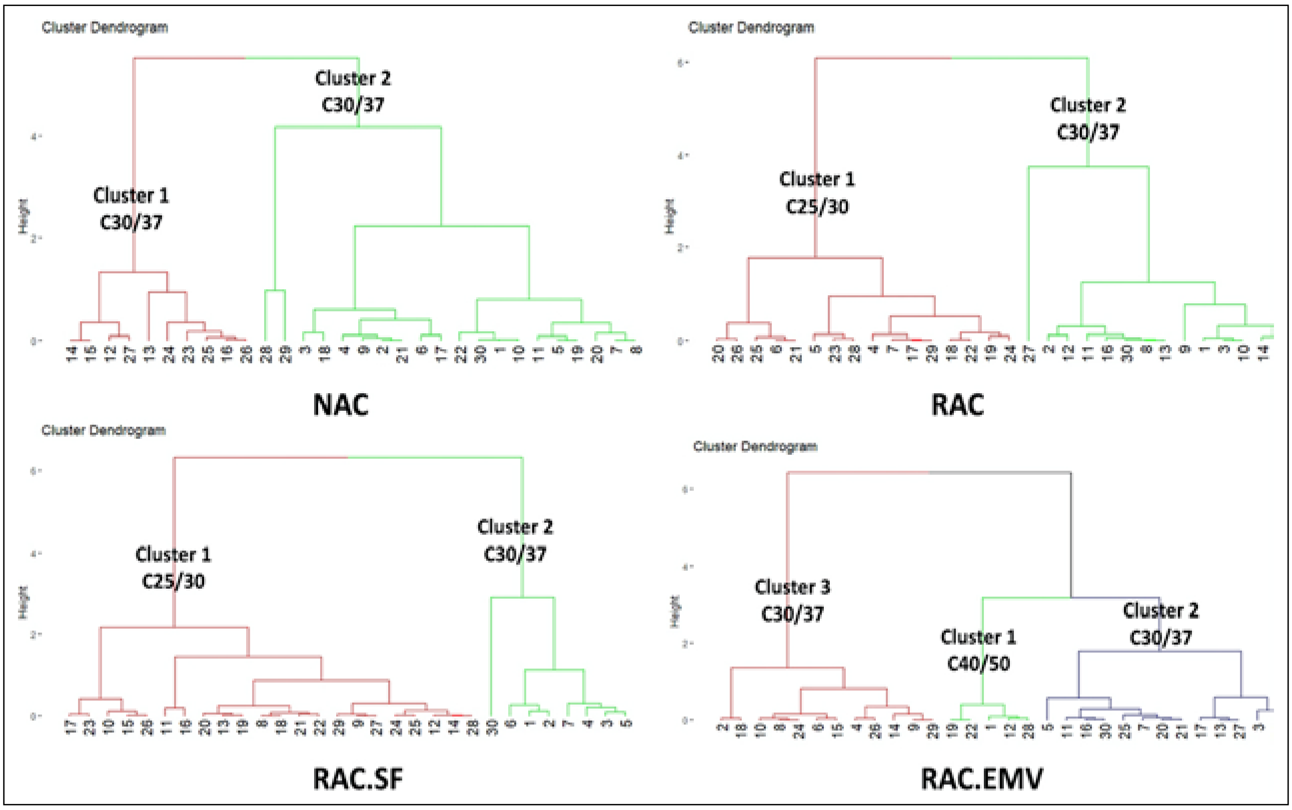

Figure 2. Hierarchical cluster analysis results (dendrograms).

$$C = \frac{x1 + x2 + x3 + ...X_n}{k} \tag{6}$$

2.3.2. Chi-Square Analysis

The Chi-square test was one of the most widely used tests among nonparametric tests in different application areas. The two most commonly used chi-square methods were tests of independence and tests of goodness. The Chi-square independence test was used to examine the relationship between categorical variables in the study. The chi-square distribution was often used to test two independent qualitative criteria. The null hypothesis (H0) states that the two criteria were independent; the research (alternate) hypothesis (HA) stated that there was a relationship between the two criteria [20].

3. RESULTS AND DISCUSSIONS

3.1. Compressive Strength Class of Concretes

The results showed that C30/37 was achieved for RAC.SF and only (Table 6). RAC.EVM has C35/45, and the result of RAC was determined as C25/30. The results presented the influence of the components and considered mixing methods. RA's weak properties (i.e., high water absorption ratio) affected the properties of concrete, decreasing the strengths (i.e., compressive strength) [21–27]. RA adhered to an old mortar (AOM) part in its body, and AOM was the key to opening the negative impact door in concrete. Hence, AOM decreased compressive strength. A question that comes to mind is: How is AOM affected? AOM with a porous structure was the response [28]. However, considering a mineral addition (i.e., SF) in the mix design may treat the strengths, increasing the compressive strength. The treatment steps of SF may be causing an additional C-S-H gel, reducing free calcium hydroxide content and filling/closing pores [29-30]. Besides, EMV responded significantly to the strengths and increased the strength and the strength class [14]. Here, the improvement of EMV may be caused by considering the aggregate concentration for RAC, which should be similar to that of NAC.

Table 6. Strength class of concretes

	RAC	NAC	RAC.SF	RAC.EVM
Strength class	C25/30	C30/37	C30/37	C35/45

NAC: Natural aggregate concrete; RAC: Recycled aggregate concrete; SF: Silica fume; EVM: Equivalent mortar volume.

3.2. Compressive Strength Class of Concretes

In this study, hierarchical cluster analysis (HCA) was applied to examine the natural structure of concretes, with visual results presented in Figure 2. This approach illustrated the strength class mapping of the measured data as clusters, facilitating comparing cluster results. Consequently, changes or constancies in strength classes could be observed, revealing the data's topology. Variations in strength within clusters can affect structural behavior under loads, particularly lateral loads such as those from earthquakes. Therefore, a detailed examination of the measured data was conducted to investigate the behavior of the concretes considered in this paper.

Table 7. Compression test results of concrete clusters

Concrete types	Cluster number	Mean of cluster
NAC	Cluster 1	42.829
	Cluster 2	46.691
RAC	Cluster 1	36.509
	Cluster 2	41.552
RAC.SF	Cluster 1	38.629
	Cluster 2	43.643
RAC.EMV	Cluster 1	57.77
	Cluster 2	53.235
	Cluster 3	47.987

NAC: Natural aggregate concrete; RAC: Recycled aggregate concrete; SF: Silica fume; EVM: Equivalent mortar volume.

Concrete strengths were classified into four groups. According to the cluster analysis results, NAC, RAC, and RAC.SF was naturally divided into two clusters each, while RAC.EMV was split into three clusters. Considering the homogeneity of bulk data, clustering data into subgroups may pose challenges. Ideally, a higher number of clusters would ensure a homogeneous distribution of units within the clusters, thereby achieving overall homogeneity in the data structure. The accuracy of the identified clusters was tested with k-means clustering, and the cluster means are provided in Table 7.

In the literature, Kılınçarslan et al. [12] conducted research on concrete with various aggregate types (trachybasalt (TB), sand and gravel (SG), limestone (L), recrystallized limestone (RL), dolomite (DO), and tephra–phonolite) to investigate clustering of strengths such as compressive strength, splitting tensile strength, and bending strength. They found that R-, L-, and SG-based concretes formed one cluster, DO- and TB-based concretes formed three clusters, and TB-based concrete formed two clusters in the test results [12]. It was reported that concretes with compressive strengths ranging from 40 to 55 MPa were obtained, with L-based concrete exhibiting a mean compressive strength of 44.26 MPa within one cluster [12]. Furthermore, the mechanical strength of aggregate and the clustering behavior of concrete properties (e.g., compressive strength) were correlated [12]. Thus, it can be inferred that RA, with lower properties than NA, may alter clustering, as evidenced by the test results. The concrete mixing process was another factor influencing clustering (Table 7).

Based on the analysis results from hierarchical cluster analysis and descriptive statistical analysis, the strength classes of the concretes were determined and categorized as lower (<20 MPa), medium (20-40 MPa), and high (>40 MPa). According to the dendrograms (Fig. 2), the clusters of concretes generally fell within the medium strength class (C30/37). However, each group exhibited distinct strength classes due to mixing method and mineral treatment variations. For instance, RAC was divided into two clusters, each corresponding to C25/30 and C30/37 strength classes, highlighting the dominant effect of RA when compared to NAC. A similar behavior was observed for RAC.SF, with each cluster also corresponding to C25/30 and C30/37 strength classes. Conversely, RAC.EMV exhibited a unique structure, where the first cluster fell within the high-strength class, and the remaining clusters were within the medium-strength class. These results suggest extensive data on the compressive strength of RAC.SF, and RAC.EMV should be thoroughly analyzed. Furthermore, the findings indicate that clustering may induce a soft floor in reinforced concrete structures and create structural elements with fluctuating strength distributions if concrete designed with RA is used.

Tanglegrams (Fig. 3) were employed to visualize the cluster structure of concretes. The graphs in Figure 3 were constructed based on the displacement of concrete units between clusters. A Tanglegram consists of a pair of dendrograms on the same set of lines, with corresponding lines in the two dendrograms connected by an edge. This allows a visual comparison of dendrograms obtained from different algorithms or experiments by linking data labels with edges. In Figure 3, the displacement of concrete units within the strength classes was analyzed. For example, upon comparison, concrete units 28 and 29, initially in cluster 2 of NAC, were found in cluster 1 of RAC. It was observed that these units shifted from the C30/37 strength class (NAC, Cluster 1) to the C25/30 strength class (RAC, Cluster 1), suggesting that the use of RA contributed to the reduction in strength class results. Another comparison involved NAC and RAC.SF. A significant shift in concrete units' location within cluster and strength classes was noted. The decrease in strength class was anticipated due to the presence of RA in RAC.SF, while the increase in strength class was attributed to adding SF.

When comparing NAC and RAC.EMV tanglegrams, it was notable that most concrete units shifted from the medium strength class (C30/37) to the high strength class (C40/50). Concrete units 28, 1, and 22, initially in NAC (Cluster 2) within the medium strength class (C30/37), moved to the high strength class when compared with RAC.EMV. This shift can be explained by the EMV design, which aims to maintain a consistent NA ratio in the total volume of RAC, providing strength through NA, which serves as a framework in concrete [8]. As a result, the decreases in strength observed in RAC were not present.EMV. However, the natural aggregate structure in RA is believed to play a role in the strength increase [28].

This study clustered concrete strengths using Euclidean distance and the central neighborhood algorithm. The accuracy of the hierarchical cluster analysis results was verified using k-means clustering. Based on the tanglegram results, a high cluster and strength class shift rate was observed between the control group (NAC) and other concrete groups (RAC, RAC.SF, and RAC.EMV).

The null hypothesis (H0) stated that the two criteria were independent. In this paper, all relationships were significant for the Chi-square hypothesis (Table 8). The significance of cluster changes was assessed using the Chi-

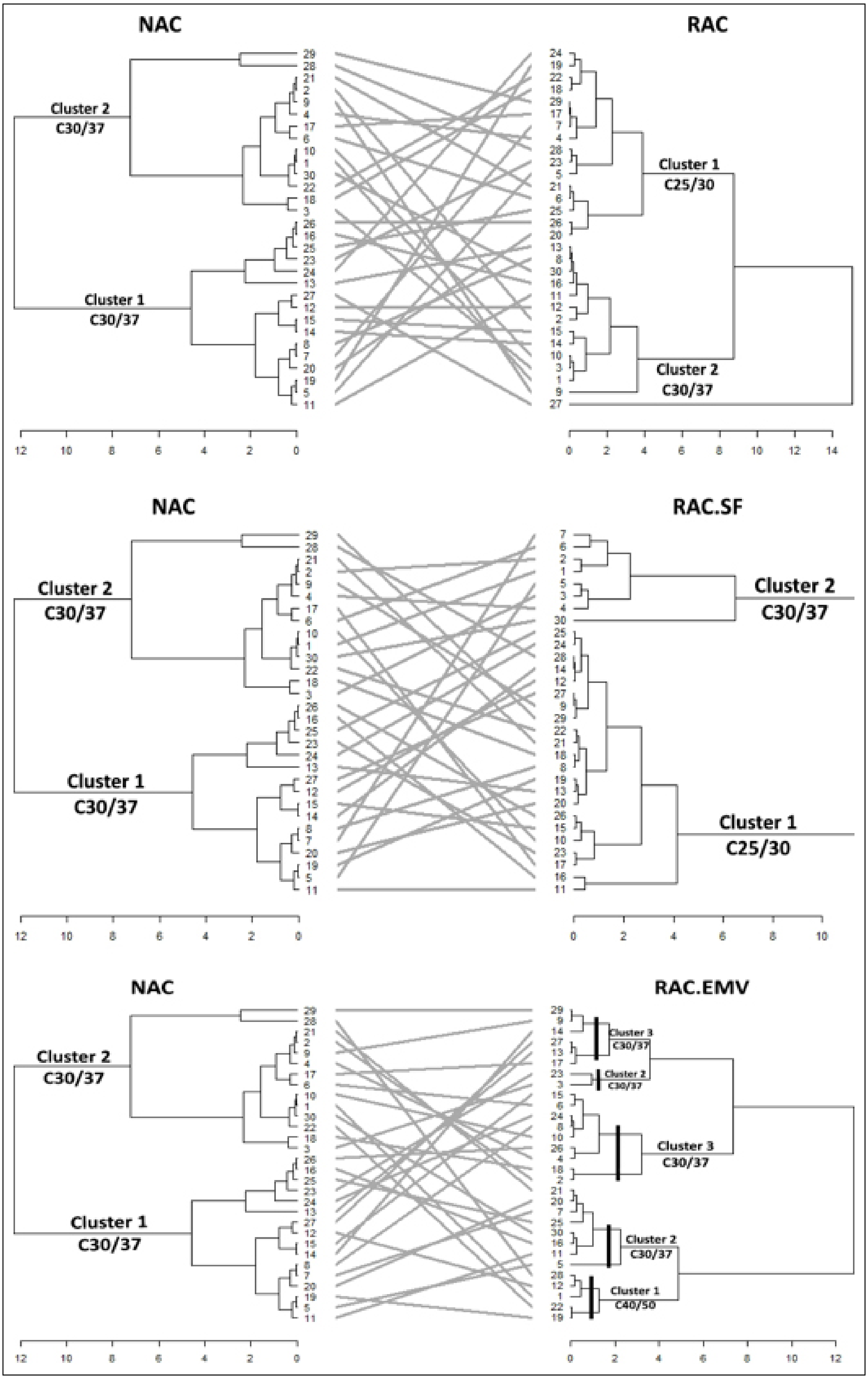

Figure 3. Comparisons of Hierarchical Cluster Analysis results with tanglegrams.

Table 8. Chi-square analysis results according to hierarchical cluster analysis

Variable relationships	Value	df	AS (2-sided)	Results
NAC and RAC	13.125	1	0.000	NAC and RAC have a statistically significant relationship (reject at α=0.05 level).
NAC and RAC.SF	6.429	1	0.011	There is a statistically significant relationship between NAC and RAC.SF (reject at α=0.05 level).
NAC and RAC.EMV	19.165	2	0.000	There is a statistically significant relationship between NAC and RAC.EMV (reject at α=0.05 level).

AS: Asymptotic significance; NAC: Natural aggregate concrete; RAC: Recycled aggregate concrete; SF: Silica fume; EVM: Equivalent mortar volume.

square test (Table 8). The variables (clusters) used in the analysis were derived from hierarchical and k-means clustering. According to the results, the Chi-square tests for all compressive strength groups were significant at the 95% significance level.

3.3. Statistical Parameters of Clusters

In the analysis of the 'Compressive Strength Class of Concretes,' the strength class of the concretes was examined individually (Table 6) and within the context of clusters (Table 7). This approach facilitates the comparison of the overall data and clustering effects on the strength class. According to the results, the targeted strength class of C30/37 was achieved for RAC—SF and NAC. However, the strength class of NAC clusters was observed to be C30/37, consistent with the overall data. This consistency did not extend to the other concretes, as their clusters exhibited different and scattered strength classes. It can be stated that the use of RA in concrete caused a decrease in compressive strength, increased scatter, and standard deviation, resulting in clusters. RA was more dominant than NA—for instance, clusters of RAC.SF included C25/30 and C30/37 strength classes, whereas the overall data for RAC.SF showed a strength class of C30/37. The use of RA in RAC appeared to introduce heterogeneity in the compressive strength data, with the clustering effect of RA being more pronounced than that of NA.

Examining the standard deviation (SD) of clusters revealed that RA increased the SD of compressive strength in clusters, while SF and EMV decreased it. The coefficient of variation (CV), defined as the standard deviation divided by the mean, assessed changes between strength classes. A low CV indicates minimal variation in the data. For NAC, the CV was 6%, with cluster 1 showing a CV of 5% and cluster 2 a CV of 2%. This indicates more significant variability in the first cluster of NAC concrete units with a medium strength class (C30/37). For RAC, the overall CV was 8%, with cluster CVs of 7% and 3%, respectively. Significant shifts were observed in the first cluster of RAC, resulting in differing strength classes: C25/30 for the first cluster and C30/37 for the second cluster.

RAC.SF exhibited some of the lowest CV values at the main (6%) and cluster levels (6% for the first cluster and 2% for the second cluster)—the first cluster of RAC.SF showed a strength class of C25/30 with higher variability, while the second cluster showed a strength class of C30/37 among the three clusters formed from RAC.EMV, low variability was a notable feature, with each sub-cluster exhibiting different strength classes. Cluster 1 had the lowest variability and a high strength class (C40/50), while clusters 2 and 3 had the same CV but different strength classes: C35/45 and C30/37, respectively.

4. CONCLUSIONS

This study aimed to investigate the clustering of the compressive strength of recycled aggregate concrete (RAC). Four concrete groups were produced under standard conditions for this experimental study. The first group included natural aggregate concretes (NAC) designed using the Absolute Volume Method (AVM) as control concretes. The second group comprised RACs designed using the Equivalent Mortar Volume Method (EVM), serving as the control for RAC. The third group consisted of RACs treated with silica fume (SF) and designed using AVM, while the fourth group comprised RACs designed with EVM. Statistical analyses were performed on the test results, including Hierarchical Cluster Analysis (HCA), strength class determination, and Chi-Square Analysis.

The introduction of recycled aggregate (RA) in RAC resulted in more significant heterogeneity in compressive strength data, increased scatter, and higher standard deviation than natural aggregate (NA). Specifically, clusters of RAC showed a broader variation in strength classes (C25/30 and C30/37) compared to NAC, which maintained a consistent strength class of C30/37. This indicates that the clustering effect of RA is more dominant than NA's. Consequently, this heterogeneity may lead to clusters in the compressive strength of concrete and variability in the measured data, potentially creating a soft floor effect in reinforced concrete structures and structural elements with fluctuating strength distributions if RAC is used.

EVM showed potential as a preferred method over mineral addition treatment for enhancing RAC. However, further investigations are warranted to explore additional concrete parameters, such as cement dosage and water-to-binder ratio, which may influence RAC's overall performance and consistency. This critical study area warrants further exploration to enhance RAC's understanding and practical application.

AUTHOR CONTRIBUTIONS

The authors contributed equally to the study.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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USE OF AI FOR WRITING ASSISTANCE

English check is made by Microsoft Copilot AI at revision stage.

PEER-REVIEW

Externally peer-reviewed.

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