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Machine Learning Models for Mechanical and Micro Structural Properties of Recycled Fine Aggregate Concrete Using Different Mixing Approaches

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ABSTRACT

The construction industry is primarily responsible for the depletion of natural resources and the disruption of environmental equilibrium due to unregulated mining activities. In this particular context, the utilization of recycled fine aggregate (RFA) derived from construction and demolition (C&D) waste presents itself as a viable solution. The conventional method of mix proportioning for RFA in concrete is not applicable in this case. The main innovation of our research lies in the fulfilment of one of the principles of circular economy, namely the reduction of carbon emissions, through the recycling of locally collected concrete waste. To tackle this issue, a novel triple mix-proportioning approach has been developed using the concepts of maximum packing density and minimum paste theory. The fresh and hardened properties were evaluated and microstructural characterization was carried out for the newly formulated mixes incorporating RFA with optimized combined aggregates. The compressive strength of concrete with recycled fine aggregate increases by 5.04% for 25% and, 21.69% for 50% replacement, and decreases by 35.44% for 100% replacement as compared to controlled concrete at the age of 28 days using the triple mixing approach. The findings indicate that replacing approximately 50% of sand with RFA is the optimal amount, as further replacement leads to a decrease in compressive strength, particularly at 100% replacement due to the presence of adhered mortar in RFA. In this study, the performance evaluation of RFA concrete has been conducted by comparing six established ML regression models and sensitivity analysis was performed to assess the variable's performance.

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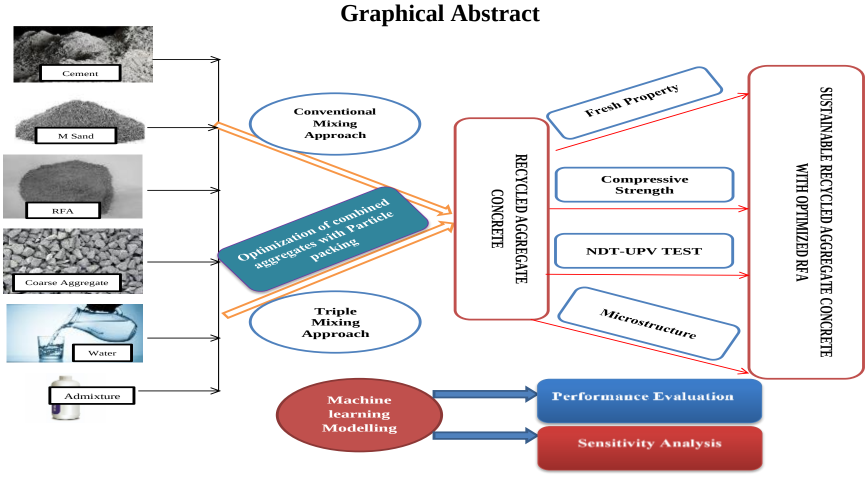
Graphical Abstract



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1. INTRODUCTION

Recently, there has been an increase in the utilization of recycled aggregate in concrete owing to its potential in curbing environmental pollution and conserving natural resources. Over the period of 2005-2013, India generated an estimated 165-175 million tons of construction and demolition (C&D) debris on an annual basis (1). The deposit of this waste material in a landfill has had detrimental effects on the ecosystem. India has put forth a series of policies aimed at promoting the use of recycled aggregates as a substitute for natural aggregates in various applications (2). The mining of M sand from rocks or quarries has also contributed to environmental hazards. The utilization of recycled coarse aggregates (RCA) in concrete has undergone extensive research in various countries and has been implemented on a global scale (3). In contemporary society, there is a growing apprehension regarding the escalating magnitude of Construction and Demolition (C&D) substances as well as the significant fraction of refuse amassing in landfills (4). Within the realm of construction, a substantial portion of refuse originates from the demolition of edifices. The exorbitant expenses associated with disposal, which encompass dumping fees and landfill taxes, coupled with the limited accessibility of disposal sites, present an opportunity for the advancement of high-performance concrete (HPC) that incorporates refuse substances as a viable alternative (5).

India has recently garnered attention for its efforts to promote sustainable materials in the construction sector. The utilization of recycled concrete brings forth a multitude of notable advantages, fostering environmental sustainability and enhancing efficiency within the industry. Primarily, it diminishes the need for natural aggregates; thereby conserving crucial resources such as gravel and sand, all while mitigating the adverse environmental effects associated with quarrying and extraction processes. Furthermore, the recycling of concrete diverts construction and demolition waste away from landfills, resulting in reduced waste and the cultivation of a circular economy approach. Additionally, the incorporation of recycled concrete as a partial substitute for natural aggregates facilitates energy conservation during concrete production, predominantly in the realm of cement manufacturing, thereby contributing to improved energy efficiency. It is also worth noting that adequately processed and integrated recycled concrete fortifies the mechanical properties of high strength concrete, culminating in structures that are more resilient and enduring.

The product's strength can be attributed to the fact that when water is added to the recycled sand, it activates some of the binding properties that the cementitious material, which had not been hydrated previously, possesses. Fine recycled concrete aggregates (RFAs) include not only the original river sand, but also a significant amount of old cement matrix. This matrix can exist either as fine particles with a high-absorption capacity or as mortar adhered to the surface of the river sand particles. The presence of this adhering cement matrix has resulted in the RFAs having a lower density, greater water absorption, and reduced hardness and strength compared to natural fine aggregates (6, 7).

The existing literature has documented that the performance of concrete is adversely affected as the proportion of recycled fine aggregate (RFA) in the concrete increases (8-10). Nevertheless, studies have demonstrated that the introduction of superplasticizers or mineral admixtures yields more favorable outcomes (11-13). For the incorporation of RFA exceeding 20%, it becomes necessary to pre-soak the aggregates in order to attain the desired workability of the concrete (14).

Relatively limited research has been conducted on concrete made with recycled fine aggregates (RFAs) due to the notable porosity and substantial water absorption of the RFAs. The elevated porosity of the preexisting cement paste results in unfavorable properties of the interfacial transition zone (ITZ) (15). The water absorption rate of the RFAs was found to be 11-13% (11, 16), which exceeded that of the natural fine aggregate, further highlighting their high porosity.

In their study, Kumar et al. (16) found that the compressive and splitting tensile strengths of the concrete were reduced by 16% and 7.0%, respectively. When using recycled fine aggregates (RFA) in high strength concrete, the reduction in compressive strength ranged from 4% to 12%, while the reduction in splitting tensile strength was 24% for concrete containing 100% RFA (11, 17). Previous studies on RFA concrete (11, 18) showed that most slump values fell within the range of 80-134 mm. However, Yang et al. (19) investigated the use of high slump RFA concrete, with a slump range of 175-200 mm, but they focused solely on normal strength RFA concrete.

The conventional method of mix proportioning for RFA concrete does not improve the concrete's performance in the absence of additives or admixtures (20). On the other hand, different mixing approaches have enhanced the performance of concrete containing recycled coarse aggregates (RCA) (21). By incorporating RCA into the concrete mix, construction companies can effectively reduce their carbon footprint and contribute to the conservation of natural resources (22). Unfortunately, there have been limited studies on the suitable mix proportioning of concrete using RFA.

Recently, an assessment was conducted on the laboratory properties of recycled aggregate concrete. Moreover, constitutive relationships were established by simulating the experimental outcomes (23) and stress-strain characteristics (24) of developed beams, utilizing the ABAQUS software. To evaluate the torsional capacity of both natural aggregate concrete (NAC) and recycled aggregate concrete (RAC) beams under pure torsion, an experimental investigation was conducted. The obtained results were subsequently validated by simulating them in the ATENA-3D simulation software (25). These types of studies demonstrate the increasing potential of recycled aggregate concrete for its structural applications (23, 25).

This necessitates the implementation of a sustainable and environmentally conscious strategy for the utilization of Recycled Fine Aggregate (RFA) in concrete. Within this framework, it is imperative to employ suitable techniques for the formulation of concrete mixes in order to maximize the efficient utilization of RFA as a substitute for river sand. The traditional method of mixing utilized in recycled aggregate concrete fails to enhance the performance of RAC. In order to address this issue, alternative mixing techniques such as the two-stage mixing approach (TSMA) and triple mixing (TM) have been implemented (26, 27). Thus, to promote sustainability and conserve natural resources, we have opted to partially substitute natural fine aggregates with recycled fine aggregates at varying levels of replacement, utilizing different mixing approaches in the preparation of concrete.

Furthermore, the results obtained for a specific recycled substance may rely on the geographic location and origin of the waste. Therefore, in order to incorporate a particular recycled fine aggregate in novel concrete mixtures for structural purposes, a thorough examination of multiple batches of the substance is necessary due to its variability and sensitivity to its source. The aim of this investigation is to assess the characteristics of locally produced RFA and explore the potential of substituting natural fine sand in concrete with recycled fine concrete aggregate. This is accomplished by considering various loading conditions through experimentation and by comparing the mechanical properties of concrete made with recycled fine aggregate to those of concrete made with natural sand.

The effectiveness of the recently formulated RFA concrete mixes is subsequently contrasted with the traditional concrete formulated according to IS 10262 (28). In this investigation, the assessment of RFA concrete performance has been carried out by comparing six well-established individual ML regression models. Moreover, statistical indicators have been utilized to compare the models. The findings imply that the ML approach shows significant potential in accurately forecasting performance. Additionally, a sensitivity analysis was conducted to evaluate the performance of the variable.

1. 1. Novelty and Research Significance

Concrete derived from recycled aggregate provides support for numerous sustainability initiatives due to its ability to conserve landfill space, manage construction waste in a more environmentally friendly manner, diminish the necessity for aggregate extraction, and mitigate pollution caused by the mining of natural aggregate. Nonetheless, the utilization of recycled aggregate concrete (RAC) remains limited as a result of insufficient advancements in the realm of testing and specifications pertaining to its production. Consequently, there is a pressing demand for further investigation and enhancements in this field.

The bulk of previous research conducted on recycled concrete aggregates (RCA) has predominantly concentrated on coarse RCA (CRCA), while significantly less progress has been made in regards to the utilization of fine RCA particles (RFA).

The primary novelty of our investigation resides in fulfilling one of the principles of circular economy, namely, the reduction of the carbon footprint, through the recycling of locally collected concrete waste. In the current study, we endeavor to overcome the drawbacks of various mix design methods, thus introducing a maximum packing density with minimal paste design concept to enhance the performance parameters of RAC in a straightforward manner. This article presents an innovative approach to the proportioning of concrete, aiming to effectively utilize RFA by replacing different percentages of river sand with a combined gradation of RFA, intermediate (10 mm) aggregate, and coarse aggregate (20 mm). Machine learning models were employed to assess the performance evaluation of formulated RFA concrete mixtures, and the conducted sensitivity analysis reveals the most significant parameter ingredient. Figure 1 shows the visual appearance of materials used in experimental program.

2. MATERIALS AND METHODS

2. 1. Material Characterization

Prior to utilization of any substance in the fabrication of recycled aggregate concrete, it is imperative to perform a comprehensive characterization. Therefore, experimental investigations were undertaken to ascertain the pertinent physical properties.

2. 1. 1. Cement

The Portland Pozzolona Cement (PPC), which was utilized in this project and obtained from a local supplier, was manufactured by Maha cement and is compliant with the IS: 1489 (Part 1) (29) standards. The characteristics of the aforementioned PPC have been enumerated in Table 1.

2. 1. 2. Natural Coarse Aggregate

The concrete utilized hard gravel that was crushed to a maximum size of 20mm. The fractions of aggregates used were divided into two categories: 20mm passing and 10mm retained at 60%, and 10mm passing and 4.75mm retained at 40%. This selection of aggregates adheres to IS: 383-2016 (30). Table

2 illustrates the properties of NCA. The coarse aggregate's sieve analysis is depicted in Figure 2.

2. 1. 3. Natural Fine Aggregates (NFA)

Throughout our study, natural fine aggregate was replaced with Manufactured sand (M-sand) obtained from a local vendor. In accordance with IS: 383-2016 (30), M-sand complies with Zone-II. Table 3 summarized the characteristics and physical properties of natural fine aggregate.

2. 1. 4. Recycled Fine Aggregate (RFA)

Recycled fine aggregate (RFA) is procured through the pulverization of construction and demolition (C&D) waste into dimensions similar to those of natural fine aggregate. RFA adheres to the standards of Zone-II as

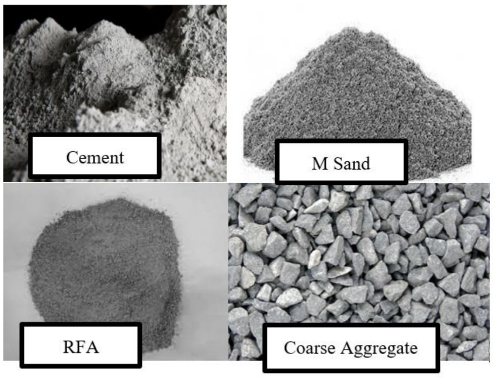

Figure 1. Visual Appearance of materials used in Experimental Program

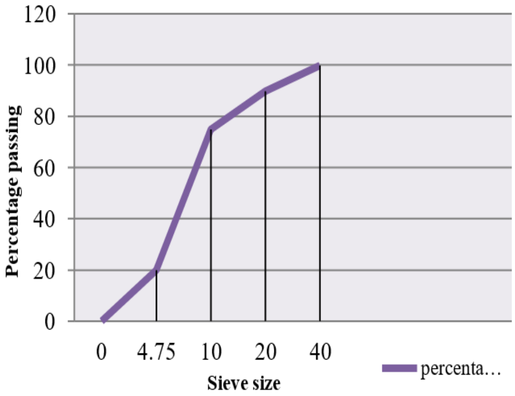

Figure 2. Sieve analysis of coarse aggregate

TABLE 1. Physical properties of cement (PPC Grade)

Sl. No.	Parameters	Test Results	Requirements as perIS:1489(part 1) (29)	Test code
1	Consistency	31		IS 4031(part 4):1988 (30)
2	Initial setting time (min)	240	Min 30 mins	IS 4031(part 5):1989 (31)
3	Final setting time (min)	270	Max 600 mins	IS 4031(part 5):1989 (31)
4	Soundness (mm)		10mm	IS:4031(part 3)-1988 (32)
5	Specific gravity	3.05	3 to 4	IS 4031-(part 3):1999 (33)
6	Fineness by Blaine's (m^2/kg)	366	Min 300	IS:4031(part 2)-1996 (34)
	Compressive Strength			
7	3 days (MPa)	23	16	IS 4031-6:1988 (35)
	7 days (MPa)	33	22	(35)

TABLE 2. Physical properties of natural coarse aggregate

Sl No.	Parameters	Test Results	Requirements as per IS:383-2016	Test IS code
1.	Specific gravity	2.8	-	IS: 2386 (Part 3) (35)
2.	Water absorption	0.5%	-	IS: 2386 (Part 3) (35)
3.	Shape test Flakiness Index Elongation Index	23.5% 16.89%	< 30%	IS: 2386(Part 1)-1963 (36)
4.	Crushing value	27.45%	<45%	IS: 2386(Part 4)-1963 (37)
5.	Angularity Number	4.9	0 to 11	IS: 2386(Part 1)- 1963 (36)
6.	Bulk density kg/m^3 (2omm passing-10mm retained) Compacted Loosely Packed (10mm passing-4.75mmretained) Compacted Loosely packed	1.59 g/ cm^3 1.51 g/ cm^3 1.55g/ cm^{3}1.51g/ cm^3	- -	IS: 2386(Part 3) (35)

TABLE 3. Physical properties of natural fine aggregate (NFA)

Sl No.	Parameters	Test Results	Test code
1	Specific gravity	2.61	IS: 2386(Part 3) (35)
2	Fineness modulus	3.01	IS: 2386(Part 1) (36)
3	Sieve Analysis	Zone-II	IS: 2386(Part 1) (36)
4	Water Absorption	7 %	IS: 2386(Part 3) (35)
5	Loose Bulk Density	1.481g/ cm^3	IS: 2386(Part 3) (35)
6	Compacted Bulk Density	1.744 g/cm^3	IS: 2386(Part 3) (35)

outlined by IS: 383-2016 (38). The attributes of RFA are outlined in Table 4. Furthermore, a mineralogical analysis of the RFA was carried out through X-Ray diffraction (XRD) analysis. The XRD graph depicted in Figure 3 clearly exhibits the presence of silica, as indicated by the hump observed between 20-352ɵ.

2. 1. 5. Particle Size Analysis of NFA And RFA The analysis of particle size for NFA, 25RFA+75NFA, 50NFA+50RFA, and RFA is appropriately delineated in Figure 4. It is noteworthy to mention that all specimens fall within zone II, as prescribed by IS: 383-2016 (38).

TABLE 4. Physical properties of recycled fine aggregate (RFA)

Sl No.	Parameters	Test Results	Test code
1	Specific gravity	2.50	IS:2386(Part3) (35)
2	Fineness modulus	2.71	IS:2386(Part1) (37)
3	Sieve Analysis	Zone-II	IS:2386(Part1) (37)
4	Water Absorption	31.25%	IS:2386(Part3) (35)
5	Loose Bulk Density	1.24g/cc	IS:2386(Part3) (35)
6	Compacted Bulk Density	1.408 g/cc	

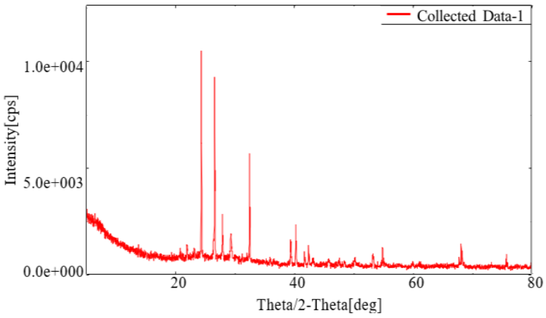

Figure 3. X-ray diffraction analysis of RFA

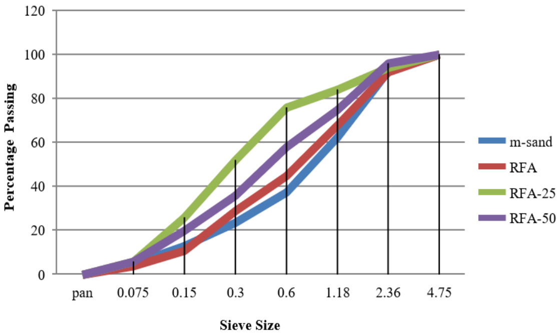

Figure 4. Particle size distribution of m sand, RFA, various replacement levels of RFA with msand

2. 1. 6. Chemical Admixture The present study utilizes a chemical admixture known as Smart Care Maximo Plast PC-200, a superplasticizer based on polycarboxylic ether.

The properties of the aforementioned chemical admixture can be found in Table 5.

2. 1. 7. Concrete Mix Proportion The concrete formulations were devised for M30 classification in compliance with IS: 10262-2019 (28), and the composition ratios are delineated in Table 6.

3. MIX APPROACH

3. 1. Conventional Mixing The present study has incorporated conventional mixing as one of the mixing

TABLE 5. Properties of chemical admixture

Parameters	Properties
Appearance	Yellow to brown liquid
Specific Gravity@27°C	1.03 to 1.08
pH	Min 6
Chloride Content	< 0.5 % by weight as per BS5075:Part1

TABLE 6. Mix proportions of controlled and recycled fine aggregate concrete mixes

Mixing Approach	Designation	Cement (kg/m^3)	M-sand (kg/m^3)	RFA (kg/m^3)	NCA (kg/m^3)		Water(kg)	Chemical Admixture	W/C
					10 mm	20 mm			
Conventional	Controlled Concrete	345	727	0	884	346	148	3.45	0.43
Triple mixing with optimized combined aggregate concept	RFA 25	326	545.25	181.75	936	365	132	2.95	0.40
	RFA 50	326	363.5	363.5	936	365	132	2.95	0.40
	RFA 100	326	0	727	936	365	132	2.95	0.40

approaches. Conventional mixing involves a sequential addition of ingredients to create a proper dry mix. Initially, half of the coarse aggregate is introduced into the mixer, followed by the addition of the dry mix and mixed for a minimum of two minutes.

Cement, fine aggregate, and the remaining coarse aggregate. The components are then thoroughly mixed to achieve a homogenous mixture. Subsequently, water and chemical admixture, such as superplasticizers, are added to the dry mix and mixed for a minimum of two of two minutes. The procedure of conventional mixing is visually represented in Figure 5.

3. 2. Triple Mixing with Optimization of Combined Aggregates

Triple mixing, a novel mixing methodology in the construction industry, was employed in our research (39). Despite its lack of widespread usage, this approach presents a promising alternative to traditional mixing techniques. In this research, a new approach is proposed for the optimal mixture design of concrete to efficiently utilize recycled fine aggregate (RFA) as a substitute for river sand. The proposed approach involves a combination of RFA, intermediate aggregate (10 mm), and coarse aggregate (20 mm) to achieve a well-packed particle arrangement with minimal paste content. The experimental procedure for achieving maximum packing density of aggregates is depicted in Figure A.1 (Provided in Appendix). The proportions of fine aggregate (FA), intermediate aggregate (IA), and coarse aggregate (CA) are determined as 40:42:18 according to the guidelines specified in IS 456 (BIS 2000), ensuring that the total percentage of aggregates adds up to 100.

Figure 5. Conventional mixing approach

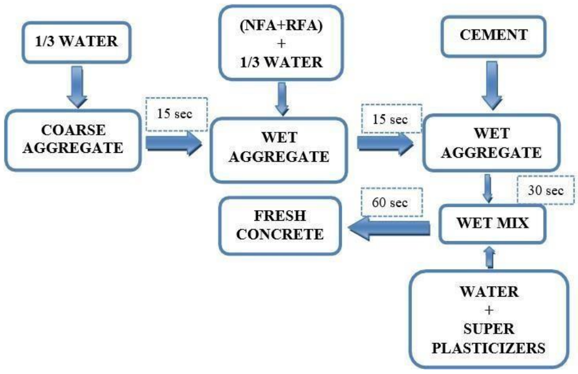

Figure 6. Triple mixing approach

To assess the effectiveness of different fine aggregates, the percentage of fine aggregate is varied from 0% to 100% in a systematic manner. For instance, if the fine aggregate constitutes 10%, the remaining 90% is divided into 63% for the intermediate aggregate and 27% for the coarse aggregate (FA + IA + CA = 10 + 63 + 27 = 100). Similarly, data sets are gathered by altering the percentage of intermediate aggregate and coarse aggregate as well. The process commences with the mixing of coarse aggregate and 1/3-part water for 15 seconds, followed by the addition of fine aggregate and RFA, which is mixed for an additional 15 seconds. Finally, cement is introduced to the wet aggregate and mixed for 30 seconds. The ultimate step in the concrete preparation process involves blending the remaining one-third portion of water with a chemical admixture and incorporating it into the wet mixture. This amalgamation must be mixed for a duration of 60 seconds to ensure optimal results. The ultimate fresh concrete product is generated after two minutes of preparation. This method of blending has proven to yield superior hardened properties, such as compressive strength, in recycled aggregate concrete when compared to traditional mixing techniques. Figure 6 depicts the triple mixing approach utilized in this process.

4. RESULT AND DISCUSSION

4. 1. Fresh Property Slump

The concrete formulations were formulated to attain a target slump of 75mm. Upon examination of Figure 7, it is evident that the consistency of the mixture, as indicated by the slump measurement, varied from 90-110mm for both the controlled concrete and recycled aggregate concrete mixtures in both the traditional and triple mixing methods. This desired degree of slump was achieved by incorporating 1% super plasticizer with an unvarying W/C of 0.43 in all the formulations.

Although the workability of RAC was marginally reduced in comparison to controlled concrete in the conventional mixing method due to the existence of surface pores and rough surface texture in RFA which necessitates more water, negligible variations were noted in the triple mixing approach for both controlled concrete and recycled aggregate concrete.

4. 2. Hardened Property: Compressive Strength

The concrete mixtures were formulated with the aim of achieving a compressive strength of 30Mpa. Upon analysis of Figure 8 and Table 7, it is evident that the compressive strength of recycled aggregate concrete (RAC) experiences a decrease of 27.89% for 25% replacement, 21.58% for 50% replacement, and 63.02% for 100% replacement of recycled fine aggregate (RFA) in comparison to controlled concrete at 7 days. Figure 9 and Table 7 illustrates that the compressive strength of RAC increases by 10.51% for 25% replacement, 10.67% for 50% replacement, and experiences a decrease of 38.71% for 100% replacement in comparison to controlled concrete at the age of 28 days, following conventional mixing approach. Notably, the compressive strength of recycled aggregate concrete increases by 5.04% for 25% replacement, 21.69% for 50% replacement, and experiences a decrease of 35.44% for 100% replacement in comparison to controlled concrete at the age of 28 days, following triple mixing approach.

The observed enhancement in compressive strength can be attributed to the particle packing of RFA. A portion of the RFA was found to be finer than natural fine aggregate, resulting in a more compact and dense concrete (40). However, a reduction in compressive strength occurs beyond a 50% replacement rate, particularly at 100% replacement, due to the presence of attached old cement mortar in RFA. The decrease in compressive strength of RAC at all replacement levels after 7 days and the increase in compressive strength of RAC at all replacement levels after 28 days can be attributed to the internal curing effect of RFA. This effect allows for the water initially absorbed inside the pores of RFA to be available at later stages for cement hydration (41, 42).

4. 3. Quality Assessment: Ultrasonic Plus Velocity (UPV) Test

The non-destructive UPV test is employed as a method for evaluating the quality of concrete. The direct approach is utilized to determine

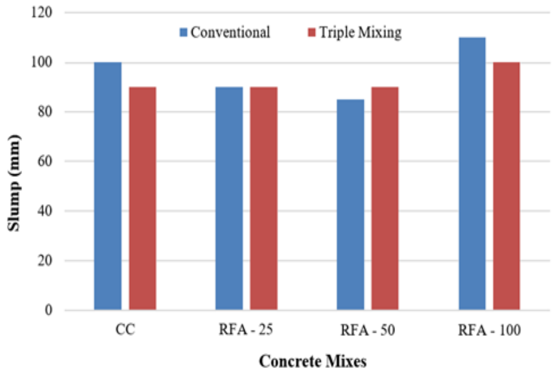

Figure 7. Slump test results of various concrete mixes

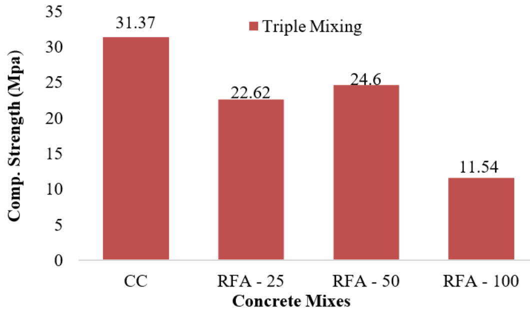

Figure 8. Graphical representation of compressive strength test results of concrete mixes at the age of 7

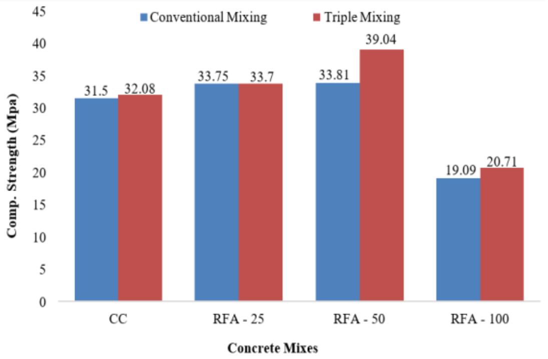

Figure 9. Graphical representation of compressive strength test results of concrete mixes at the age of 28 days

TABLE 7. Compressive strength test results of concrete mixes

Specimen	Triple Mixing 7 days (MPa)	Triple Mixing 28 days (MPa)
CC	31.37	31.15
RFA 25%	22.62	33.75
RFA 50%	24.60	33.81
RFA 100%	11.54	19.09

UPV values for various concrete mixes. Table 8 illustrate the UPV results of all specimens that were cured for 28 days. The UPV values ranged from 9500 to 10000 m/sec, regardless of whether the concrete was made with controlled or recycled aggregates, and whether conventional or triple mixing approaches were employed.

It was observed that the UPV values increased as the RFA content increased, regardless of age. These findings demonstrate that the UPV value falls within the excellent category, as prescribed in Table 1 IS 516 (Part 5)/(section1):2018 (43).

4. 4. Micro Structural Analysis

Microstructural analysis was conducted on all concrete mixes of 28-day cured specimens. Subsequently, the cured specimens underwent compression testing, and the ruptured specimens were examined using a scanning electron microscope.

4. 4. 1. Micro Structural Analysis of Controlled Concrete

Figures 11a and 11b serve to depict the microstructure of controlled concrete through the utilization of conventional mixing and triple mixing methods. The former figure showcases the formation of hydrated calcium silicate hydrate (CSH) gel and the rupture of concrete specimen occurring through the aggregate. Similarly, Figure 11b demonstrates the formation of hydrated CSH gel in contrast to Figure 10a. It is worth noting that the formation of CSH gel plays a pivotal role in the enhancement of cube specimen strength.

Proportioning of materials

Mixing of concrete ingredients using Pan mixer

Slump Test for workability

Compaction of concrete using table vibrator

Casting of Specimens

Curing of specimens

Cube Compression testing

Failure cube specimen

Figure 10. Salient process involved in the experimental program

TABLE 8. Ultrasonic pulse velocity test results of concrete mixes

Sample	Ultrasonic Pulse Velocity at 28 days age for		Grading
	Conventional Mixing (m/s)	Triple Mixing (m/s)	
CC	9500	9750	Excellent
RFA25	9709	9417.6	Excellent
RFA50	10000	10000	Excellent
RFA 100	10000	10000	Excellent

4. 4. 2. Micro Structural Analysis of Recycled Aggregate Concrete at 25% Replacement of RFA

Figures 11a and 11b depict the microstructure of Recycled Aggregate Concrete (RAC) at a 25% replacement of Recycled Fine Aggregate (RFA) by means of the conventional mixing approach and the triple mixing approach, respectively. The formation of Calcium

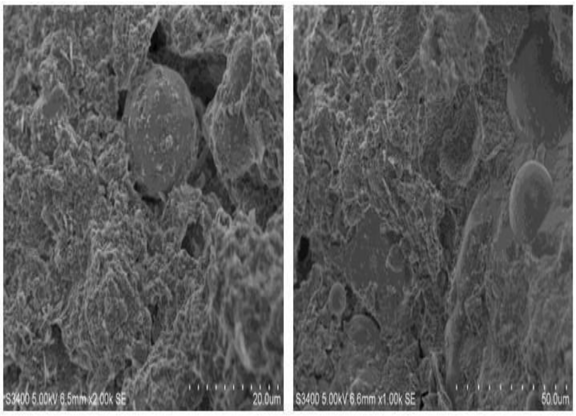

Figure 11a. Microstructure of controlled concrete by conventional mixing

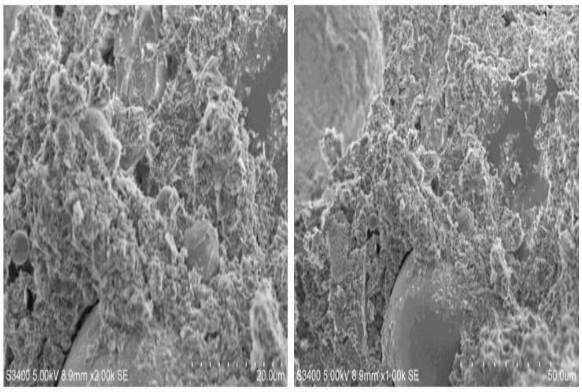

Figure 11b. Microstructure of controlled concrete by triple mixing

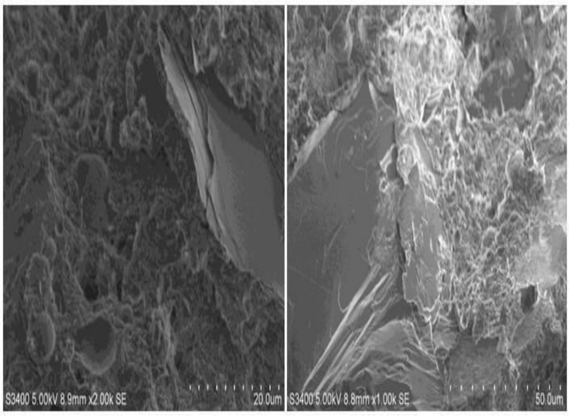

Figure 12a. Micro structure of recycled aggregate concrete with 25% RFA by conventional mixing

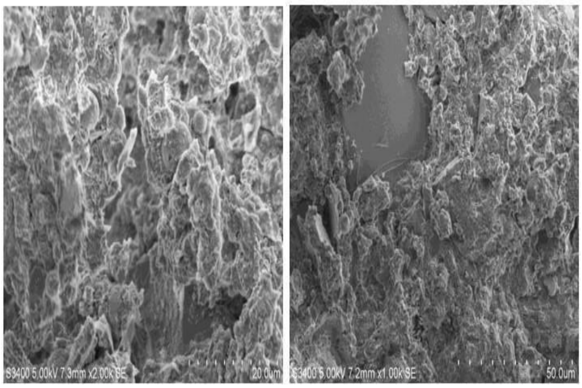

Figure 12b. Microstructure of recycled aggregate concrete with 25% RFA by triple mixing

Silicate Hydrate (CSH) gel was observed in both Figures 12a and 12b, along with the observation of hexagonal platelets of calcium hydroxide in both conventional and triple mixing approach specimens. A denser microstructure was observed in Figures 12a and 12b in comparison to the controlled concrete illustrated in Figures 11a and 11b. This denser microstructure is the reason for the increase in strength observed in RAC in comparison to controlled concrete for both mixing approaches.

4. 4. 3. Micro Structural Analysis of Recycled Aggregate Concrete at 50% Replacement of RFA

Figures 13a and 13b depict the microstructure of Recycled Aggregate Concrete (RAC) at 50% replacement of Recycled Fine Aggregate (RFA) in both conventional and triple mixing approaches, respectively. It is noteworthy that the formation of hydrated Calcium Silicate Hydrate (CSH) gel is more pronounced in RAC at 50% RFA replacement in comparison to conventional concrete, as evidenced by Figures 11a and 11b. Moreover, a denser microstructure was observed in RAC at 50% RFA replacement, which surpasses that of other concrete mixes, including recycled aggregate concrete at 25% replacement, as shown in Figures 12a and 12b. The analysis of the microstructure is in alignment with the compressive strength results obtained.

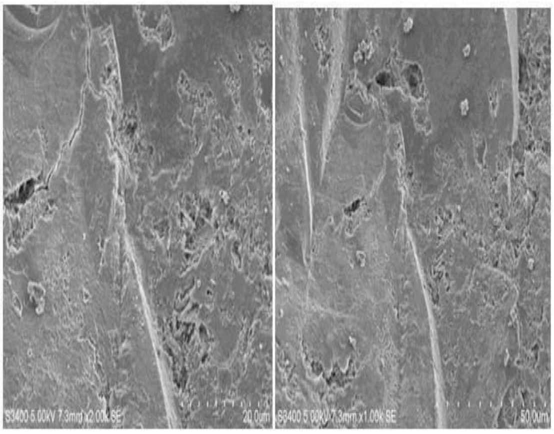

Figure 13a. Microstructure of recycled aggregate concrete with 50% RFA by conventional mixing

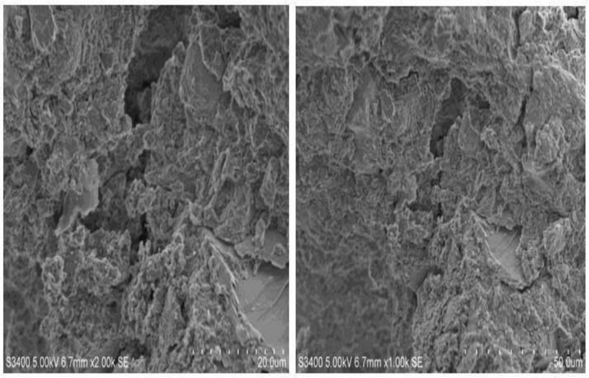

Figure 13b. Microstructure of recycled aggregate concrete with 50% RFA by triple mixing

5. 6. Proposed Machine Learning Models

Six machine learning (ML) methodologies have been integrated to optimize the RFA concrete for relationship modeling. The six ML algorithms utilized in this study (44), include Support Vector Regression (SVR), Decision Tree Regression (DTR), Gradient Boosting Regression (GBR), Artificial Neural Network (ANN), Bayesian Ridge Regression (BRR), and Kernel Ridge Regression (KRR).

Typical network structure of SVR is represented in Figure 14 (44).

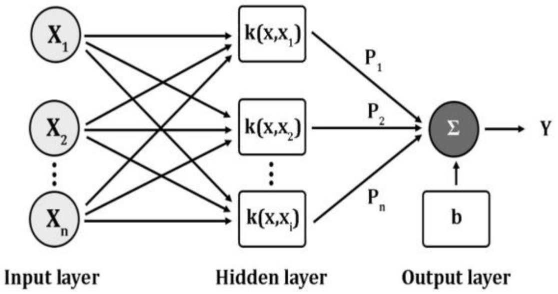

Figure 14a. Network of support vector machine (44)

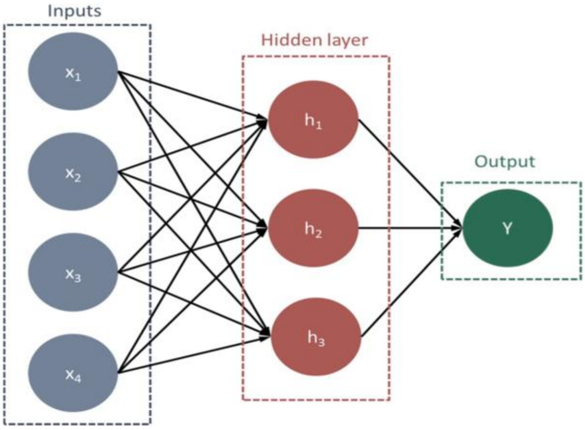

Figure 14b. Function of ANN (38)

5. 6. 1. Dataset

The implementation of the prediction utilizes a dataset collected from 423 specimens, each with distinct influencing variables. In order to facilitate the training process, this dataset is divided into two separate subsets: a training set and a testing set. The training set is utilized to train the machine learning models and adjust the hyper-parameters, while the testing set is reserved for performance evaluation (44, 45). The training set is selected at random and the remaining data comprises the testing set. It is noteworthy that the same training set is employed in all six machine learning models presented in this paper, with the testing set being consistent across each model as well. Specifically, 70% of the entire dataset is allocated to the training set, with the remaining 30% being assigned to the testing set (46, 47).

5. 6. 2. Comparison of Integrated ML Approaches

In this section, a total of six Machine Learning (ML) techniques that have been integrated are analyzed and their predictive performance on the testing set is thoroughly compared and discussed. The evaluation of performance is carried out utilizing the Mean Squared Error (MSE) value and the R value (47).

Figure 15 presents the Mean Squared Error (MSE) and R value of six Machine Learning (ML) models on the testing set. Analysis of Figure 15(a) indicates that Gradient Boosting Regression (GBR) is the optimal prediction model in terms of MSE. When GBR is utilized, the MSE values of the training and testing sets

TABLE 9. Dataset for performance prediction

Particular	Concrete type	Input Variables	Size	Output variable
Dataset	RFA Concrete	Cement, Water, Fine aggregate, Coarse aggregate, Admixture	423	Compressive strength

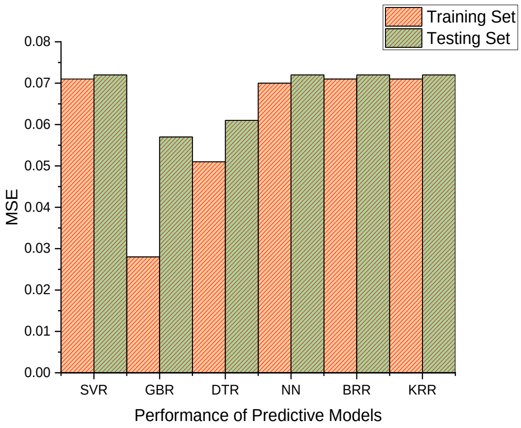

Figure 15a. Predictive performance of models – MSE

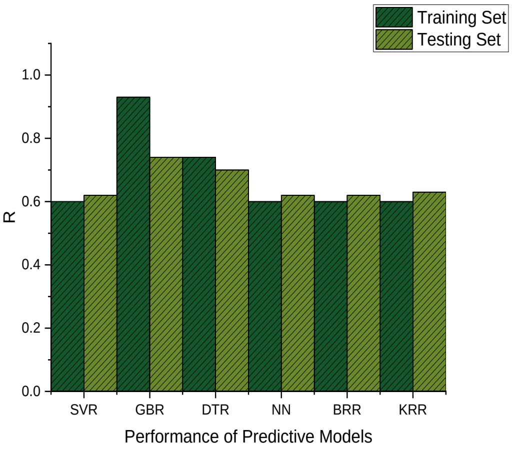

Figure 15b. Predictive performance of models - R

are 0.028 and 0.057, respectively. Meanwhile, Decision Tree Regression (DTR) also exhibits commendable performance, with the training and testing MSE values of 0.051 and 0.061, respectively. The remaining four models demonstrate a comparable MSE of approximately 0.7. In Figure 15(b), GBR surpasses the other five models with respect to R value.

The training set and testing set exhibit R values of 0.93 and 0.74, respectively. DTR also showcases a favorable predictive ability with R values of 0.74 and 0.7 for training and testing sets, respectively. The remaining four models have R values that are approximately 0.6. SVR, NN, BRR, and KRR exhibit a testing set R value that is slightly higher than their respective training set R values. In contrast, the performance of BRR is comparatively inadequate when evaluated using MSE and R values, as opposed to DTR and GBR. Based on Figure 15, it is evident that DTR and GBR are more effective in predicting the effective performance of the RFA concrete.

5. 6. 3. Sensitivity Analysis Sensitivity analysis was conducted utilizing equation number 1 in order to comprehend the relative contribution of input parameters towards the compressive strength. Within the equation, $f_{max}(yi)$ and $f_{min}(yi)$ represent the highest and lowest values of predicted parameter, respectively, corresponding to the i^{th} domain. It is important to note that all input variables were maintained as constants, utilizing their mean values (48-50).

$$S = \frac{f_{max}(y_i) - f_{min}(y_i)}{\sum_{n}^{n=j} N_i} \tag{1}$$

Equation 1 is employed to all the datasets to estimate the sensitivity of input variable on the predictor. The parameter such as SP, Cement Content, Water content, age of the specimens was found to have higher influence on compressive strength compared to other materials used as depicted in Figure 16. The least sensitive variable is fine aggregate and coarse aggregate.

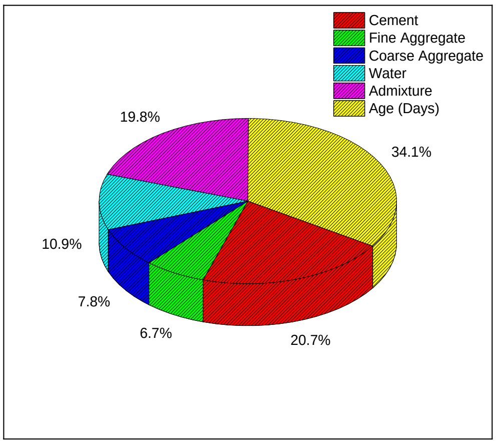

Figure 16. Sensitivity analysis of all datasets

6. CONCLUSION

This manuscript delineates an innovative technique for determining the appropriate mixture proportions of recycled fine aggregate concrete. This technique employs a combined particle packing method, resulting in a refined performance of the concrete that is based on recycled fine aggregate.

(1) The physical properties of Recycled Fine Aggregate (RFA) are akin to those of natural fine aggregate, albeit with a notable distinction in water absorption. Specifically, the water absorption of RFA is 6.25% greater than that of M sand.

(2) The mix proportioning that has been developed displays a negligible impact on the workability of concrete. The workability of concrete experiences a decline as the percentage of RFA content increases, as a result of the presence of previously adhered mortar.

(3) At the age of 7 days, an increase in the percentage of replacement of RFA resulted in a decrease in the compressive strength of RAC, in comparison to controlled concrete.

(4) As the proportion of RFA increases, there is a corresponding decrease in the mechanical characteristics. Nevertheless, this decline in properties can be mitigated by incorporating specific additives into the concrete blends through the utilization of this recently developed mixture ratio. In the triple mixing approach, the compressive strength of RAC increased with a proportional increase in the percentage of replacement of RFA, up to 50%, in contrast to controlled concrete.

(5) The compressive strength of recycled aggregate concrete increases by 5.04% for 25% replacement,

21.69% for 50% replacement and decreases by 35.44% for 100% replacement as compared to controlled concrete at the age of 28 days for triple mixing approach. This increase in compressive strength was attributed to the filler effect of RFA, part of which was finer then natural fine aggregate, making concrete more compact and denser. But beyond 50%, there is reduction in compressive strength particularly at 100% replacement due to the presence of adhered mortar in RFA.

(5) According to IS: 516 (Part 5)/(section1):2018, the UPV test values for both controlled concrete and RAC are classified as excellent.

(6) The utilization of 50% replacement of recycled fine aggregate (RFA) in concrete, through the triple mixing approach, resulted in the observation of the formation of a hydrated calcium silicate hydrate (CSH) gel and a highly compact microstructure. This was in contrast to the other concrete mixes studied.

(7) The verification of the optimal Machine Learning (ML) model's performance is conducted through the utilization of Mean Squared Error (MSE) and the R value, resulting in the attainment of minimum MSE values for all six ML models. The findings indicate that the ML approach has immense potential for the accurate prediction of performance. The optimal Gradient Boosting Regression (GBR) model exhibits commendable performance on both the training and testing sets. The achievement of a low MSE and high R value between the predicted CCP values and the experimental results on both the training and testing sets signifies that the optimal GBR model outperforms the other five models in terms of accurate prediction.

(8) Sensitivity analysis has demonstrated that the variables, such as Superplasticizer, Cement, Water, and Age (day), exert a substantial influence on compressive strength, subsequently followed by the pozzolan material. The variable displaying the lowest sensitivity is fine aggregate, along with coarse aggregate.

The article serves as a basic framework for the proper utilization of C& D waste for the development of sustainable concrete which solves environmental issues. With the methodology adopted here, minimum paste and maximum packing density concept will be an answer for reduced carbon footprint in the days to come.

Limitations: The article emphasizes the advantageous utilization of concrete based on RFA (Recycled Fine Aggregate) through the application of a unique mix proportioning technique. This technique allows for a 50% replacement of RFA in the concrete, resulting in enhanced performance when combined with the inclusion of mineral admixtures. Subsequent research endeavors should explore the potential contributions and efficiencies of alternative cementitious binders when employing RFA concrete. Also, cost effectiveness of this novel mixing method should also be explored in future studies.

Our study can be utilized as a fundamental framework for furthering the implementation of RCA in the process of preparing concrete for the purpose of sustainable construction.

Future Research

The authors acknowledge the significance of additional investigation pertaining to the topic in order to establish a logical framework for specifying recycled aggregate and concrete. To enumerate a handful of prospective domains, there exists a necessity to formulate procedures for designing concrete mixtures, analyze recycled concrete at the micro-structural level, and scrutinize the enduring capacity of said concrete, especially in arduous surroundings.

7. ACKNOWLEDGEMENTS

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Persian Abstract

چکیده

صنعت ساخت و ساز در درجه اول مسئول کاهش منابع طبیعی و برهم زدن تعادل زیست محیطی به دلیل فعالیت های غیرقانونی معدن است. در این زمینه خاص، استفاده از سنگدانه های ریز بازیافتی (RFA) که از ضایعات ساخت و ساز و تخریب (D&C) به دست می آید خود را به عنوان یک راه حل مناسب نشان می دهد. روش مرسوم تناسب مخلوط برای RFA در بتن در این مورد قابل اجرا نیست. نوآوری اصلی تحقیقات ما در تحقق یکی از اصول اقتصاد دایره ای، یعنی کاهش انتشار کربن، از طریق بازیافت زباله های بتن جمع آوری شده محلی است. برای مقابله با این موضوع، یک رویکرد جدید نسبت مخلوط سه گانه با استفاده از مفاهیم حداکثر چگالی بسته بندی و تئوری خمیر حداقل توسعه داده شده است. خواص تازه و سخت شده ارزیابی شد و خصوصیات ریزساختاری برای مخلوط‌های تازه فرموله‌شده حاوی RFA با سنگدانه‌های ترکیبی بهینه‌سازی شده انجام شد. مقاومت فشاری بتن با سنگدانه های ریز بازیافتی ٥/٠٤ درصد برای ٢٥ درصد و ٢١/٦٩ درصد برای ٥٠ درصد جایگزینی افزایش می یابد و ٣٥/٤٤ درصد برای جایگزینی ١٠٠ درصد در مقایسه با بتن کنترل شده در سن ٢٨ روز با استفاده از رویکرد اختلاط سه گانه کاهش می یابد. . یافته ها نشان می دهد که جایگزینی تقریباً ٥٠ درصد ماسه با RFA مقدار بهینه است، زیرا جایگزینی بیشتر منجر به کاهش مقاومت فشاری، به ویژه در جایگزینی ١٠٠ درصد به دلیل وجود ملات چسبیده در RFA می شود. در این مطالعه، ارزیابی عملکرد بتن RFA با مقایسه شش مدل رگرسیون ML انجام شده و تحلیل حساسیت برای ارزیابی عملکرد متغیر انجام شد.

Appendix

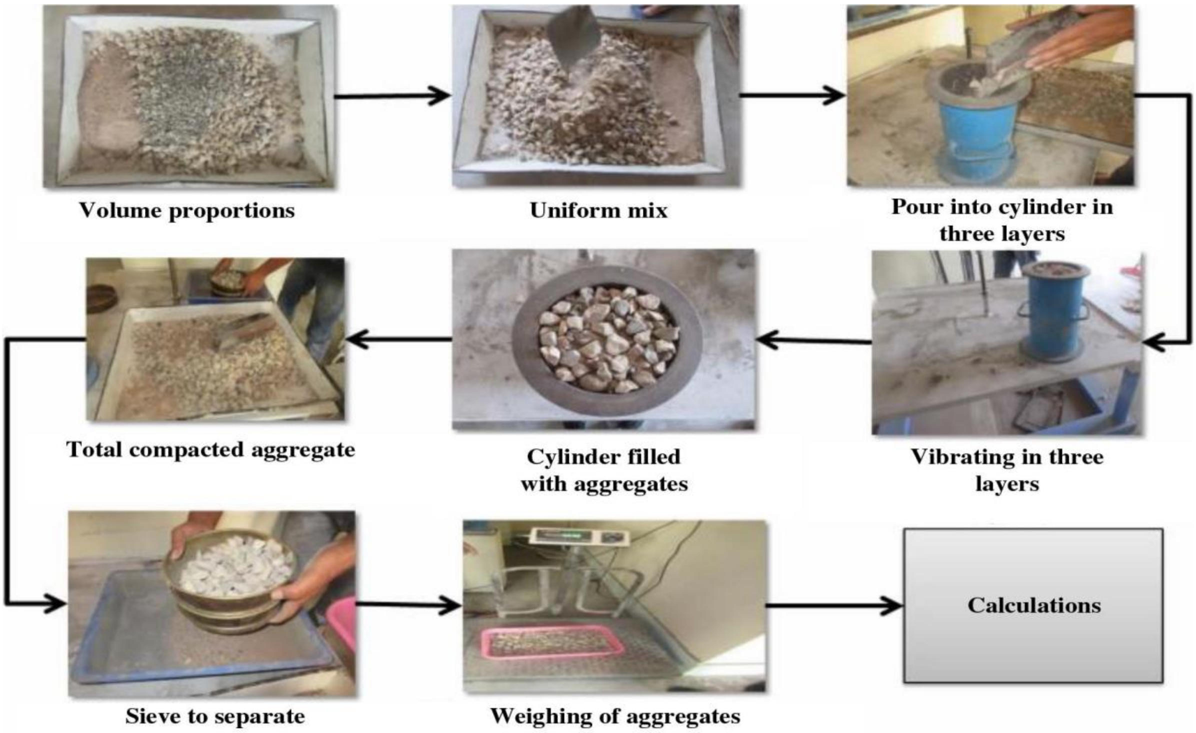

Figure A.1. Experimental procedure to determine particle packing density [33]