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Original Article

A Hybrid Approach for Predicting Properties of Recycled Aggregate Concrete using Experimental Testing, Artificial Neural Networks, and Regression Modeling

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Abstract *- This paper looks into mechanical and fresh characteristics of Recycled Aggregate Concrete (RAC) using a broad experimental and predictive modeling approach. An extensive experimental database on 144 concrete mixes was established, including compressive strength of between 15 and 40 MPa. The aggregate that was also used as a replacement for the natural coarse aggregate was Recycled Aggregate (RA), which was used as a percentage of 0-100 with an increment of 20 percent. Three specimens were cast and also tested for every mix, with the average values of compressive strength, slump, and density recorded. The main aim of the research was to measure the effect of adding RA content on the concrete performance as well as to establish valid prediction models with the help of Artificial Neural Networks (ANNs) and regression analysis, which were executed and approved with the help of MATLAB and Python, respectively. The results of the experiments showed a definite and gradual decrease in the concrete properties as the content of RA increased. Compressive strength was decreased by up to around 35 percent, slump by an average of 38 percent, and density by close to 15 percent at full replacement of the RA relative to the comparison mixes with natural aggregates. These tendencies could be explained by high porosity, lower interfacial transition zones, and greater water uptake of recycled aggregates. An ANN model that uses tansig activation was created, and its predictive accuracy is very high, with the error margins of about ±2.5 MPa when predicting compressive strength, ±3 mm when predicting slump, and ±25 kg/m3 when predicting density. The ANN model showed good statistical results, and the R2 values were found to be higher than 0.976, and the MSE and RMSE values were low in all the outputs. Python-based regression models showed moderately good predictive performance with comparatively somewhat larger errors and lower R2 values. These were further verified by the correlation matrices, actual versus predicted plots, and residual analysis that indicated the higher robustness and stability of the ANN method. Overall, the findings demonstrate the efficiency of data-driven modeling methods, especially ANN, to predict RAC properties in an accurate way and justify sustainable concrete mix design.*

***Keywords* -** *ANN, Regression analysis, Predictive modeling, Compressive strength, Slump, Density*.

1. Introduction

The ever-increasing need for sustainable construction materials has greatly raised the concern of reusing construction and demolition wastes, especially by using recycled aggregates in the manufacture of concrete. Recycled aggregate concrete has become a viable substitute for traditional concrete on the basis of its high potential in terms of environmental impact, which is the minimization of consumption of natural aggregates, reduction of landfill disposal, and reduction of the carbon footprint of construction operations. In spite of these benefits, the use of recycled aggregate concrete is yet to be introduced widely, largely because of the uncertainties surrounding its mechanical and fresh characteristics. Such uncertainties are due to the fact that recycled aggregates are more variable in nature, with a relatively low quality in most instances, than the natural aggregates [1, 2].

The construction and demolition industry is eating up colossal amounts of natural resources and creating billions of tonnes of solid waste on an annual basis, which includes concrete rubble, ceramics, Polyethylene Terephthalate (PET), glass, and slag. Simultaneously, about thirty-two billion tons of natural aggregates are mined on an annual basis throughout the world. The associated environmental burden of these activities can be reduced by replacing natural aggregates with recycled aggregates obtained from construction and demolition waste. The paper has also reviewed past literature in terms of recycled aggregate application in concrete manufacturing, indicating the primary challenges and prospects of the subject matter. Despite the fact that recycled aggregates normally lower the performance of fresh and hardened concrete as compared to that of natural aggregates, such decreases are usually minor in cases where replacement amounts are maintained at below 30. In addition, a number of mitigation techniques have been suggested to reduce the performance losses. However, more needs to be done to enhance the process of recycled aggregate processing, as well as encourage the global standardization of the use of such methods in the process of concrete production [2].

In order to comprehend the effects of Recycled Aggregate (RA) on the performance of concrete, it is necessary to consider the concrete mix design of the Recycled Aggregate Concrete (RAC) and modify it to the peculiarities of RA. In contrast to natural aggregates, recycled ones are normally of high water absorption, reduced density, and more variable because of the presence of old mortar that is attached. These natural variations have a great influence on fresh and hardened concrete properties such as workability, strength development, and durability. As a result, techniques of conventional mix design that have been created to work with natural aggregate concrete cannot be directly applied to RAC. Such a rational RAC mix design approach should consequently take into account the physical and mechanical characteristics of RA, adequate modification in water content and cement dosage, optimal mix in aggregates, and the potential use of admixtures to satisfy performance needs. The optimization of RAC mix design is a serious study issue to have reliable, consistent, and sustainable manufacturing of concrete using recycled material [3, 4].

There is consistent evidence in the literature of prior experimental research that incorporation of recycled aggregates has a significant effect on critical concrete properties, including compressive strength, workability, and density. These are mainly due to the fact that recycled aggregates are more porous, and the interfacial transition zones, as well as water absorption, are higher. Due to this fact, the recycled concrete behavior must be predicted reliably in order to support its application in non-structural and structural applications. The classical empirical and analytical models, however, tend to be very inaccurate in the complex nonlinear interactions of mixed constituents and concrete performance [5-7]. The methods of data-driven modeling have been actively gaining popularity in civil engineering studies in recent years. In concrete technology, artificial neural networks have been very effective in nonlinear modeling of input variables and response in terms of output. These methods, together with regression analysis, form an all-round framework that allows both accurate prediction and clear interpretation of material behavior. However, few studies have embraced the system of experimental investigation, modelling of artificial neural networks, and regression analysis to provide a systematized evaluation of recycled concrete performance [8].

The present research bridges this gap in research by developing an extensive experimental and predictive modeling framework of recycled aggregate concrete. A comprehensive experimental program is combined with advanced artificial neural network modeling to provide the nonlinear behavior of RAC properties, and regression analysis performed through the Python platform gives additional statistical understanding and model interpretation. The research also reinforces its analysis by correlation analysis, actual-versus-predicted, and residual analysis, providing a serious study of model accuracy and reliability.

The novelty of the present study is that it has an integrated structure in the sense that it combines experimental testing, together with machine learning and regression-based prediction methods, to give a full evaluation of the properties of recycled concretes. Through systematic comparison of experimental findings with the predictions of artificial neural networks and regression, the study provides useful information on the performance of the models, uncertainty of predictions, and applicability of the two models in engineering. This contribution helps the creation of predictive tools that can be trusted and makes the wider adoption and recycled aggregate concrete sustainable in its design.

2. Literature Review

Globally, the construction industry depends on concrete as the best material due to its ability to provide the required strength and durability to buildings, roads, in addition to bridges and other infrastructure. The large-scale concrete construction activity creates significant environmental issues since it consumes natural resources and emits significant amounts of greenhouse gases into the air. The production of conventional concrete with natural aggregates and Portland cement has a significant impact on the current environmental issues [1, 2]. RCA is a sustainable solution of natural aggregates because it is based on construction and demolition waste products. RCA reuse helps in preserving resources and eliminating wastage, and the cyclical economy model. When RCA is added, the mechanical properties are not consistent due to high levels of porosity and low levels of density and bound mortar. RCA offers a wide variety of properties that bring in unpredictability, limiting the widespread application in construction [1, 4, 9]. Determining the mechanical properties of recycled concrete is based on experimental methods. Recycled concrete can only be tested experimentally, which is time-consuming and costly, and in addition, not possible at preliminary design stages [3, 4]. Recycled aggregates of concrete were researched in new construction [6]. The strength properties are the most important properties of RCA; these properties were studied in numerous works [5, 6]. The environmental effect of RCA was also examined [10-12]. Moreover, recycled concrete aggregate was also explored as an alternative material to be employed in construction as a sustainable material [9].

The identification of nonlinear relationships between the variables of concrete mix and the mechanical performance results is a data-oriented approach based on Artificial Neural Networks [9]. Another study explores the performance degradation mechanism of RAC effectively and provides specific recommendations on how to improve its performance [13]. The reduced resistance and structural performance of Recycled Aggregate Concrete (RAC) members are evaluated with a detailed study, which introduces a numerical method to test the members. The material model was adjusted towards RAC and subsequently tested to be valid with experimental data of RAC beams and columns. Depending on the grade of RA, the structural performance of RAC beams and columns was determined and compared to NAC. Lastly, a coefficient of adjustment of RAC member to maintain structural performance until a normal aggregate concrete member was suggested [14].

Furthermore, there is comprehensive research on a new technique to enhance the mechanical strengths and durability of Recycled Aggregate Concrete (RAC) by bio-mineralization and fiber reinforcement. This study is unique in that the synergistic combination of Basalt Fibers (BF), Polyvinyl Alcohol (PVA) fibers, and bacterial self-healing functions will be used to improve the performance of the RAC. The experimental findings have shown that fiber-reinforced RAC has better compressive and splitting tensile strength than the traditional RAC [15].

The first and second cycle recycle properties of Recycled Concrete Aggregate (RCAs), including their upcycling capacity, were investigated. Hence, commercially available NAs and RCA1 were tested against lab-manufactured RCA2, both coarse and fine, which came as a result of further recycling of the First-generation Recycled Aggregate Concrete (RAC1). Extensive tests were conducted on morphology, physical, mechanical, and microstructural tests to give a good understanding of the differences between RCA2 and RCA1. Microstructure observations verified the porous structure of RCA2, which is due to more adherence to old mortar, several weak interfaces, and several microcracks than the ones found in RCA1, and hence, caution is required when using coarse RCA2 in the upcycling of sustainable construction. [16]. An extensive literature review on the use of Recycled Concrete Aggregate (RCA) and Recycled Aggregate Concrete (RAC) in construction, with the focus on structural applications and finding out the challenges and opportunities of RCA/RAC materials in the construction industry in Southeast Asia, was conducted. The article critically evaluates the physical and mechanical performance of RCA and RAC in structural applications as a first step and first time of possible standardization of RCA/RAC in Southeast Asia. Different measures to enhance the performance of the RAC elements were suggested and deliberated. The key results and limitations of past studies are critically addressed, and additional research requirements are also outlined [17].

The other study considers the mechanical properties of Recycled Aggregate Concrete (RAC) in relation to Normal Aggregate Concrete (NAC), paying attention to the impact of the fine and coarse aggregate replacement ratio. All mixes were made using a consistent mix ratio and a water-to-cement (w/c) ratio. Compressive strength and splitting tensile strength of different concrete types of varying replacement percentage of fine and coarse aggregate were tested at 7-day and 28-day curing ages. The results have shown that RAC, and more so at elevated replacement rates, is more appropriate for non-structural or low-load-bearing activities in pavement sub-bases, walkway slabs, partition walls, and low-strength concrete blocks [18].

An extensive test of the properties and performance of RAC, including fresh-state properties, mechanical behavior, and durability in harsh environmental conditions, is conducted. It also outlines the major measures to enhance the quality of RACs that may be implemented, which are pre-treatment of recycled aggregates, addition of Supplementary Cementitious Materials (SCMs) like Fly Ash (FA) and Silica Fume (SF), and fiber reinforcement to improve the performance of mechanical and durability. According to works of Life Cycle Assessment (LCA), RAC would tremendously decrease embodied energy and greenhouse gas emissions, which promotes the concept of the circular economy. However, there are a number of obstacles that do not enable the extensive use of RAC they including incoherent standards, ignorance among stakeholders, and performance prediction uncertainty. This paper reveals the gaps in research that are critical, especially in the design of reliable mix design methods, long-term field performance assessment, and new recycling technologies. The conclusion of the review is that under conditions of specific research and standardized quality control, it is possible to consider that RAC will become an inalienable component of sustainable construction practices in the world and will provide the environment with positive benefits, along with the beneficial effects on the economy [1].

To support the holistic perspectives of technology, ecology, and economics, a review study was conducted to give a detailed analysis of RCA, its characteristics, uses, and general sustainability values. It also discusses the production of RCA, its mechanical and durability properties, and its effects on the environment. Moreover, it examines the different uses of RCA, including road construction materials, pavement bases, and concrete materials, in light of their life cycle performance and economic factors. This review indicates that systematic data collection is required, and it can be used to design concrete mixes automatically [3]. Indeed, as compared to natural aggregate performance, RCA is worse, but it is now widely applied to concrete production as a sustainable solution following the rising practice of construction waste in the world. In order to address these constraints, there have been a number of mechanisms and additional Supplementary Cementitious Materials (SCMs) that have been explored in the recent past. A research examines the hybrid action of natural fiber coconut and activated fly ash (mechanically and chemically) on the performance of Recycled Concrete Aggregate (RCA). The research has immense capabilities of promoting sustainable developmental trends in high-performance structural concrete, especially in areas that focus on green building solutions [19].

Even though ANNs have proven to be successfully applied to the problems of civil engineering and the prediction of material properties, the use of ANNs to assess the characteristics of recycled concrete remains underutilized. The study develops an ANN model for training various recycled concrete mixes to achieve reasonable predictions of strength properties. The study applies ANN to give improvements in the concrete mix design in terms of better, cost-effective, and eco-friendly practices.

The study will reveal that forecasts by ANN can reduce the need to conduct long and costly laboratory tests, especially during the commencement of structural design. These models will provide the engineers with accurate and fast calculations, which will be used to determine whether to use recycled concrete or not, thereby facilitating effective, sustainable, and economical construction practices. In addition, this research is likely to contribute to the existing literature that aims to introduce the concepts of artificial intelligence into the scope of civil engineering and materials science. The modeling solutions developed along with the chosen dataset will give a starting point based on which the researchers can elaborate further work on making recycled concrete more acceptable across the board of structural use [12, 13].

Additionally, the existing literature shows that recycled concrete using Recycled Concrete Aggregate (RCA) is an effective method of recycling concrete that reduces construction and demolition wastes, preserves natural resources, and reduces environmental effects caused by concrete production. Some of the scientific studies have investigated the mechanical properties of the recycled concrete materials, although experimenting on various proportions and curing conditions of compressive strength, tensile strength, and flexural strength. Recycled Concrete Aggregate (RCA) results in uneven mechanical results since the mortar is left on the pieces to form more pores and undermine the bonding of the pieces. The existing empirical models, along with the regression techniques, cannot provide precise forecasts of recycled concrete mechanical properties [20, 21].

In the past few decades, Artificial Neural Networks (ANNs) have become a critical supporting technology in concrete technology since they enable researchers to come up with data-driven models of relationships between non-linear material responses. The advantage of ANNs lies in their ability to identify the association of many variables at once, and hence, high-quality concrete performance prediction is achieved when the mix design and curing regime, as well as the material structure, vary. There has been an application of ANN models in estimating compressive strength, slump, modulus of elasticity, and durability indicator in the last two decades. The models are useful where there is intricate data and unforeseen materials used in the constructions that are characterized by incorporating additional cementitious materials, other substitute aggregates, and recycled components.

ANNs have been shown to be useful in sustainable construction through the learning process based on past experiences and extrapolating the forecasts to unexplored mixes that reduce the cost of experimentation and accelerate material selection. The ANNs have superior performance capabilities to the traditional models in the sense of their capability to model these complex relationships [8]. Artificial intelligence as a means of research was applied to concrete with recycled coarse aggregate using the experimental results as data driven input parameters to use machine-learning algorithm (support vector machine) and three ensemble machine-learning algorithms to predict the splitting tensile strength [8] The predictive outcome of ANN was the percentage that showed the best prediction of the volcanic tuff aggregate to generate lightweight concrete.

The artificial neural networks were used in the prediction of concrete dynamic properties. Also, the idea of ANN was employed to forecast the physical and mechanical characteristics of the concrete using glass aggregate [22]. The application of Expanded Polystyrene particles in lightweight concrete to determine their compressive strength and density was also studied using ANN [22].

The literature review included in this research gives a detailed discussion of the latest and up-to-date studies concerning the recycled concrete aggregate and recycled aggregate concrete. It includes experimental, analytical, and data-intensive modelling research that is concerned with the mechanical, fresh, and physical performance of RAC, mix design strategies, durability considerations, and sustainability. The novel trends in machine learning implementation, such as artificial neural networks and regression-based prediction tools, are also discussed, with special consideration for current research in concrete technology. Generalizing findings of numerous modern sources, this review provides the sound scientific background of the current study and clearly states the gaps in the knowledge, which prompt the proposed experimental and modelling framework.

3. Experimental Program

3.1. Experimental Program Framework

The objective of the experimental program was to conduct the investigation systematically on how the recycled aggregate content affects the performance of a Recycled Aggregate Concrete (RAC) material. Six concrete mixture series were formulated by substituting natural coarse aggregate with Recycled Aggregate (RA) at replacement ratios starting with 0% and ending with 100% in each case, with each replacement ratio developed by 20% weight of coarse aggregate. The reason why all these replacement levels have been chosen was to include both partial and complete replacement scenarios and to generate a complete picture of the progressive impacts of RA incorporation. The methodology employed enabled the determination of gradual alterations in mechanical and fresh characteristics of concrete with a rise in the RA content, thus providing a credible experimental foundation for the following analytical and predictive modeling.

The proportions of the concrete mixes were determined using the traditional design processes, and the mix design parameters were listed in Table 1. The range of concrete strengths on which the experimental program was conducted spanned between 15 and 40MPa to reflect the normal level of performance that would be expected when using the concrete in the structural and non-structural recycled concrete. One hundred and forty-four concrete mixes were developed, prepared, and experimented with, each having varying proportions of recycled aggregate as shown in Table 1. Three standard 150mm cubes were cast and cured under controlled conditions for each separate mix. Following the prescribed curing time, test of all cubes was carried out during compression, and the mean compressive strength of the three specimens was documented as the representative compressive strength of that mix. This was done to guarantee the stability and reliability of the values of strength to be used in future statistical and ANN-based predictions.

3.2. Materials

The experiment program involved the use of standard concrete-making materials and Recycled Concrete Aggregates (RCA) to compare the mechanical and fresh properties of the recycled concrete mixes. Ordinary Portland Cement (OPC) meeting the ASTM C150 [23] parameters was taken as the main binder. The natural fine and coarse aggregates have been obtained at the local quarries and have been chosen to meet the grading requirements of ASTM C33 [24]. Coarse aggregates that had been recycled would then be crushed on a tested concrete specimen, sieved, washed, and dried to provide uniformity and remove as much adhered mortar as possible. All mixtures were done using potable water that was fit to mix and cure concrete [25]. A commercially available superplasticizer that complied with the requirements in ASTM C494 [26] was used where necessary to provide similar workability across mixes. Specific gravity, absorption, and the particle size distribution of the materials were also described before mixing to ascertain the accuracy of the mix design and reliability of the further performance test.

The workability was tested by carrying out slump tests immediately after mixing ASTM C143 [27]. Concrete specimens were poured and allowed to dry under the normal lab conditions, and at the age of 28 days, compressive strength was determined by testing the same. Measures of density were taken as well on models according to ASTM C 138 [28]. The proportions of all of the concrete mixes were kept at a constant ratio of 0.45 water-cement to maintain consistency in the hydration conditions and to separate the impact of the incorporation of recycled aggregates on the performance of the concrete. Having a constant water-cement ratio also enabled significant comparisons across mixes with varying levels of recycled aggregate replacement since the differences in strength, workability, and density could be explained by the properties and composition of the recycled aggregate as opposed to variations in the water demand of mixes.

Table 1. Mix proportions and material quantities for all recycled concrete mixtures

Group	RA %	Fc MPa	Cement Kg/m^3	CA Kg/m^3	FA Kg/m^3	CA/FA	RA Kg/m^3	W Kg/m^3	SP Kg/m^3
C15-G1	0	15	200	1050	700	1.5	0	90	4.2
	20	15	200	840	700	1.5	210	90	4.2
	40	15	200	630	700	1.5	420	90	4.2
	60	15	200	420	700	1.5	630	90	4.2
	80	15	200	210	700	1.5	840	90	4.2
	100	15	200	0	700	1.5	1050	90	4.2
C15-G2	0	15	200	1120	700	1.6	0	90	4.2
	20	15	200	896	700	1.6	224	90	4.2
	40	15	200	672	700	1.6	448	90	4.2
	60	15	200	448	700	1.6	672	90	4.2
	80	15	200	224	700	1.6	896	90	4.2
	100	15	200	0	700	1.6	1120	90	4.2

C15-G3	0	15	200	1190	700	1.7	0	90	4.2
	20	15	200	952	700	1.7	238	90	4.2
	40	15	200	714	700	1.7	476	90	4.2
	60	15	200	476	700	1.7	714	90	4.2
	80	15	200	238	700	1.7	952	90	4.2
	100	15	200	0	700	1.7	1190	90	4.2
C15-G4	0	15	200	1260	700	1.8	0	90	4.2
	20	15	200	1008	700	1.8	252	90	4.2
	40	15	200	756	700	1.8	504	90	4.2
	60	15	200	504	700	1.8	756	90	4.2
	80	15	200	252	700	1.8	1008	90	4.2
	100	15	200	0	700	1.8	1260	90	4.2
C20-G1	0	20	220	1110	740	1.5	0	99	4.5
	20	20	220	888	740	1.5	222	99	4.5
	40	20	220	666	740	1.5	444	99	4.5
	60	20	220	444	740	1.5	666	99	4.5
	80	20	220	222	740	1.5	888	99	4.5
	100	20	220	0	740	1.5	1110	99	4.5
C20-G2	0	20	220	1184	740	1.6	0	99	4.5
	20	20	220	947.2	740	1.6	236.8	99	4.5
	40	20	220	710.4	740	1.6	473.6	99	4.5
	60	20	220	473.6	740	1.6	710.4	99	4.5
	80	20	220	473.6	740	1.6	947.2	99	4.5
	100	20	220	0	740	1.6	1184	99	4.5
C20-G3	0	20	220	1258	740	1.7	0	99	4.5
	20	20	220	1006.4	740	1.7	251.6	99	4.5
	40	20	220	754.8	740	1.7	503.2	99	4.5
	60	20	220	503.2	740	1.7	754.8	99	4.5
	80	20	220	251.6	740	1.7	1006.4	99	4.5
	100	20	220	0	740	1.7	1158	99	4.5
C20-G4	0	20	220	1332	740	1.8	0	99	4.5
	20	20	220	1065.6	740	1.8	266.4	99	4.5
	40	20	220	799.2	740	1.8	532.8	99	4.5
	60	20	220	532.8	740	1.8	799.2	99	4.5
	80	20	220	266.4	740	1.8	1065.6	99	4.5
	100	20	220	0	740	1.8	1332	99	4.5
C25-G1	0	25	240	1155	770	1.5	0	108	4.4
	20	25	240	924	770	1.5	231	108	4.4
	40	25	240	693	770	1.5	462	108	4.4
	60	25	240	462	770	1.5	693	108	4.4
	80	25	240	231	770	1.5	924	108	4.4
	100	25	240	0	770	1.5	1155	108	4.4
C25-G2	0	25	240	1232	770	1.6	0	108	4.4
	20	25	240	985.6	770	1.6	246.4	108	4.4
	40	25	240	739.2	770	1.6	492.8	108	4.4
	60	25	240	492.8	770	1.6	739.2	108	4.4
	80	25	240	246.4	770	1.6	985.6	108	4.4
	100	25	240	0	770	1.6	1232	108	4.4
C25-G3	0	25	240	1309	770	1.7	0	108	4.4
	20	25	240	1047.2	770	1.7	261.8	108	4.4
	40	25	240	785.4	770	1.7	523.6	108	4.4
	60	25	240	523.6	770	1.7	785.4	108	4.4
	80	25	240	261.8	770	1.7	1047.2	108	4.4

	100	25	240	0	770	1.7	1309	108	4.4
C25-G4	0	25	240	1386	770	1.8	0	108	4.4
	20	25	240	1108.8	770	1.8	277.2	108	4.4
	40	25	240	831.6	770	1.8	554.4	108	4.4
	60	25	240	554.4	770	1.8	831.6	108	4.4
	80	25	240	277.2	770	1.8	1108.8	108	4.4
	100	25	240	0	770	1.8	1386	108	4.4
C30-G1	0	30	260	1155	770	1.5	0	117	5.1
	20	30	260	924	770	1.5	231	117	5.1
	40	30	260	693	770	1.5	462	117	5.1
	60	30	260	462	770	1.5	693	117	5.1
	80	30	260	231	770	1.5	924	117	5.1
	100	30	260	0	770	1.5	1155	117	5.1
C30-G2	0	30	260	1232	770	1.6	0	117	5.1
	20	30	260	985.6	770	1.6	246.4	117	5.1
	40	30	260	739.2	770	1.6	492.8	117	5.1
	60	30	260	492.8	770	1.6	739.2	117	5.1
	80	30	260	246.4	770	1.6	985.6	117	5.1
	100	30	260	0	770	1.6	1232	117	5.1
C30-G3	0	30	260	1309	770	1.7	0	117	5.1
	20	30	260	1047.2	770	1.7	261.8	117	5.1
	40	30	260	785.4	770	1.7	523.6	117	5.1
	60	30	260	523.6	770	1.7	785.4	117	5.1
	80	30	260	261.8	770	1.7	1047.2	117	5.1
	100	30	260	0	770	1.7	1309	117	5.1
C30-G4	0	30	260	1386	770	1.8	0	117	5.1
	20	30	260	1108.8	770	1.8	277.2	117	5.1
	40	30	260	831.6	770	1.8	554.4	117	5.1
	60	30	260	554.4	770	1.8	831.6	117	5.1
	80	30	260	277.2	770	1.8	1108.8	117	5.1
	100	30	260	0	770	1.8	1386	117	5.1
C35-G1	0	35	290	1125	750	1.5	0	130.5	5.75
	20	35	290	900	750	1.5	225	130.5	5.75
	40	35	290	675	750	1.5	450	130.5	5.75
	60	35	290	450	750	1.5	675	130.5	5.75
	80	35	290	225	750	1.5	900	130.5	5.75
	100	35	290	0	750	1.5	1125	130.5	5.75
C35-G2	0	35	290	1200	750	1.6	0	130.5	5.75
	20	35	290	960	750	1.6	240	130.5	5.75
	40	35	290	720	750	1.6	480	130.5	5.75
	60	35	290	480	750	1.6	720	130.5	5.75
	80	35	290	240	750	1.6	960	130.5	5.75
	100	35	290	0	750	1.6	1200	130.5	5.75
C35-G3	0	35	290	1275	750	1.7	0	130.5	5.75
	20	35	290	1020	750	1.7	255	130.5	5.75
	40	35	290	765	750	1.7	510	130.5	5.75
	60	35	290	510	750	1.7	765	130.5	5.75
	80	35	290	255	750	1.7	1020	130.5	5.75
	100	35	290	0	750	1.7	1275	130.5	5.75
C35-G4	0	35	290	1350	750	1.8	0	130.5	5.75
	20	35	290	1080	750	1.8	270	130.5	5.75
	40	35	290	810	750	1.8	540	130.5	5.75

	60	35	290	540	750	1.8	810	130.5	5.75
	80	35	290	270	750	1.8	1080	130.5	5.75
	100	35	290	0	750	1.8	1350	130.5	5.75
C40-G1	0	40	340	1125	750	1.5	0	153	7.5
	20	40	340	900	750	1.5	225	153	7.5
	40	40	340	675	750	1.5	450	153	7.5
	60	40	340	450	750	1.5	675	153	7.5
	80	40	340	225	750	1.5	900	153	7.5
	100	40	340	0	750	1.5	1125	153	7.5
C40-G2	0	40	340	1200	750	1.6	0	153	7.5
	20	40	340	960	750	1.6	240	153	7.5
	40	40	340	720	750	1.6	480	153	7.5
	60	40	340	480	750	1.6	720	153	7.5
	80	40	340	240	750	1.6	960	153	7.5
	100	40	340	0	750	1.6	1200	153	7.5
C40-G3	0	40	340	1275	750	1.7	0	153	7.5
	20	40	340	1020	750	1.7	255	153	7.5
	40	40	340	765	750	1.7	510	153	7.5
	60	40	340	510	750	1.7	765	153	7.5
	80	40	340	255	750	1.7	1020	153	7.5
	100	40	340	0	750	1.7	1275	153	7.5
C40-G4	0	40	340	1350	750	1.8	0	153	7.5
	20	40	340	1080	750	1.8	270	153	7.5
	40	40	340	810	750	1.8	540	153	7.5
	60	40	340	540	750	1.8	810	153	7.5
	80	40	340	270	750	1.8	1080	153	7.5
	100	40	340	0	750	1.8	1350	153	7.5

4. Methodology

The research approach combines three elements: (1) Experimental testing as a means of collecting data, (2) ANN modelling, and (3) Regression analysis conducted in Python. The input parameters that were included in the dataset were the percentage of RCA, the content of cement, the content of water, the proportion of coarse and fine aggregate, and the proportion of water to cement. The products were compressive strength (f_c), slump, and density.

4.1. Artificial Neural Network Modeling

The ANN model has been developed in MATLAB using forward backpropagation. The activation function (hyperbolic tangent sigmoid tansig) was chosen in the hidden layers as this activation function can be used to model nonlinear responses. In order to prevent overfitting, it was divided into the training, validation, and testing subsets. The optimization of the number of neurons, training periods, and learning rates was used as a method to optimize the model and achieve the minimum error in prediction. The tanh activation function or hyperbolic tan or tansig, an activation function, is one of the most popular nonlinear neural network activation functions, and it is commonly used in neural networks, especially as a hidden layer activation function. It maps the input values to the range (-1, 1), hence a zero-centred function that is more likely to change towards convergence on average is achieved in training compared to non-zero-centred functions like the logistic sigmoid, as shown in Figure 1. The tanh S-shaped and smooth curve allows the network to capture complex nonlinear relationships, and its zero symmetry does not allow gradient updates to be unstable. Just like other sigmoid-type functions, tanh can be malevolent with the problem of the vanishing gradient, where the inputs reach saturation levels, resulting in very small gradients. This is a weakness, but tanh remains a very powerful and popular activation function in most network architectures.

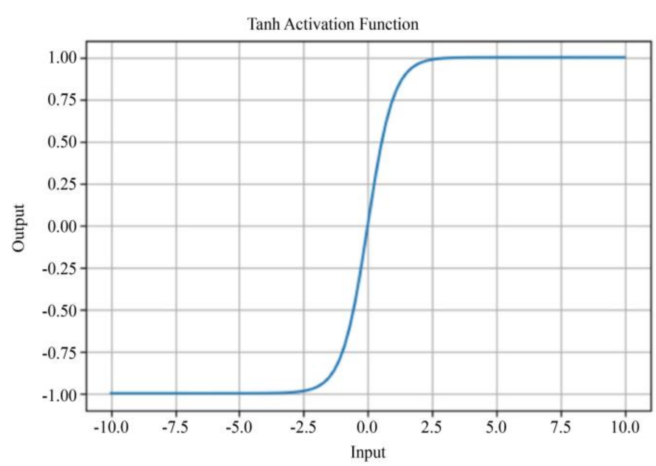

Fig. 1 (Tanh) Tansig activation function

4.2. Regression Analysis

Regression was used to develop equations of mathematical relationships between the input mixture parameters and the resultant mechanical and fresh properties of recycled aggregate concrete. The statistical method allows the intention to measure the contribution of each variable to the total behavior of the concrete, and then predictive models can be constructed based on the experimental results. In the present research, Python was used as the main computing language because it has good scientific libraries such as NumPy, pandas, and scikit-learn, which can provide efficient data processing, model testing, and performance analysis services. Python-based regression models were created to obtain the optimal fits to compressive strength, slump, and density, and the best-fit models were used to calculate the key performance indicators, including the coefficient of determination (R^2), Mean Absolute Error (MAE), Mean Squared Error (MSE), and the Root Mean Squared Error (RMSE). Such a scheme guaranteed a reproducible, transparent, and statistically sound interpretation of the experimental data.

5. Results and Discussion

5.1. Experimental Results Overview

It was found that the mechanical and fresh properties of concrete decrease with an increase in RA%. Compressive strength reduced with increasing percentage of RA was attributed to the inferior and loosely packed recycled aggregates when compared to the natural ones. The slump value also was reduced with an increasing RA% that represents low workability due to the higher water absorption capacity and rough texture of the recycled aggregates. The density of concrete also decreased with the incorporation of RA, due to the lower specific gravity and higher void ratio of recycled aggregate. The result of all strength, slump, and density experimental tests for macro-mixing proportions is summarized in Table 2.

Table 2. Experimental, ANN, and regression analysis results

Group	RA %	Experimental Results			ANN Results			Regression Results		
		Fc MPa	Slump mm	Density Kg/m³	Fc MPa	Slump mm	Density Kg/m³	Fc MPa	Slump mm	Density Kg/m³
C15-G1	0	15.10	180	2285	15.7	183.5	2293.2	15.40	182	2287
	20	14.60	167	2281	14.7	167.8	2290.2	14.80	167	2284
	40	13.75	144	2275	13.6	151.4	2285.8	13.55	148	2279
	60	12.69	133	2265	12.5	132.1	2273.2	12.15	133	2266
	80	10.87	126	2259	10.2	115.7	2260.6	10.53	124	2259
	100	9.82	110	2248	9.6	102.1	2260.7	9.73	106	2251
C15-G2	0	15.22	178	2287	15.3	179.8	2293.0	15.49	178	2289
	20	14.69	165	2283	14.6	163.2	2289.7	14.98	164	2285
	40	13.97	142	2277	13.9	146.1	2285.0	13.88	142	2281
	60	12.89	126	2269	12.8	127.3	2275.4	12.78	126	2269
	80	11.12	107	2261	10.9	109.9	2264.9	10.87	108	2262
	100	10.01	96	2255	9.8	97.8	2260.8	10.13	97	2254
C15-G3	0	15.05	176	2280	16.6	177.5	2299.1	15.56	175	2285
	20	14.55	160	2276	14.5	160.0	2295.4	14.75	159	2281
	40	13.69	139	2269	13.6	142.4	2285.8	13.89	137	2268
	60	12.62	122	2260	12.4	122.4	2280.5	12.55	121	2264
	80	10.82	103	2252	10.6	103.9	2271.3	10.82	102	2258
	100	9.89	92	2246	9.7	93.2	2255.4	10.12	91	2248
C15-G4	0	14.89	173	2274	15.1	175.1	2305.1	14.89	173	2278
	20	14.43	157	2268	14.6	156.3	2291.5	14.83	155	2273
	40	13.61	133	2259	13.5	138.4	2291.2	13.91	135	2269
	60	12.41	115	2250	12.9	117.7	2285.2	12.56	115	2255
	80	10.33	98	2242	10.2	100.4	2271.8	9.88	98	2248
	100	9.65	89	2234	9.4	89.7	2267.3	10.06	89	2236
C20-G1	0	21.21	182	2432	21.4	182.5	2392.8	21.82	182	2438
	20	20.14	176	2426	20.5	169.8	2391.3	19.89	176	2424
	40	19.09	154	2417	19.3	149.0	2384.8	19.75	154	2412
	60	17.81	133	2415	18.1	128.9	2385.9	17.36	133	2405
	80	15.91	111	2407	15.9	111.8	2358.9	15.46	111	2395
	100	14.21	98	2403	14.2	97.5	2358.8	14.39	98	2388

C20-G2	0	21.32	179	2433	21.2	178.6	2392.9	21.65	176	2425
	20	20.31	170	2427	20.1	165.1	2391.1	20.81	167	2419
	40	19.65	150	2419	19.5	143.4	2384.3	20.02	147	2411
	60	17.11	126	2412	17.01	123.8	2374.4	16.94	124	2405
	80	15.34	106	2401	15.2	99.7	2381.9	15.21	103	2392
	100	13.98	91	2398	14.5	90.7	2363.4	13.73	90	2388
C20-G3	0	21.18	178	2428	21.1	176.1	2399.3	21.45	175	2429
	20	19.98	165	2422	19.9	161.7	2397.1	20.12	163	2425
	40	18.92	143	2416	19	139.4	2385.4	19.12	141	2412
	60	17.42	119	2408	17.1	118.7	2379.7	18.16	120	2398
	80	15.72	99	2397	15.2	99.4	2370.3	15.25	98	2385
	100	14.01	88	2392	13.8	93.1	2361.8	13.79	90	2381
C20-G4	0	19.98	179	2421	21	173.6	2405.7	20.23	176	2425
	20	19.31	161	2414	19.4	157.8	2393.5	19.69	161	2416
	40	17.89	138	2401	17.6	135.2	2391.0	18.36	136	2405
	60	17.12	112	2394	16.9	113.6	2385.0	17.05	113	2402
	80	1543	92	2388	15.2	95.5	2371.0	15.65	93	2391
	100	13.69	81	2382	13.2	84.0	2366.1	14.15	79	2385
C25-G1	0	25.79	177	2451	26.5	179.6	2487.1	26.23	178	2456
	20	24.75	155	2446	25.1	162.6	2483.7	24.87	158	2459
	40	23.73	135	2439	24	140.2	2469.0	23.99	138	2446
	60	21.14	118	2433	21	120.6	2463.8	21.52	116	2439
	80	19.34	99	2428	19.1	103.0	2450.7	19.69	96	2433
	100	17.02	88	2422	17.2	88.2	2450.3	17.54	87	2426
C25-G2	0	25.98	175	2453	27.2	175.7	2487.6	26.11	178	2458
	20	24.89	152	2448	25.9	157.8	2483.7	25.57	154	2448
	40	23.88	131	2441	24.4	135.4	2476.6	23.96	133	2457
	60	21.43	114	2437	21.1	115.3	2466.5	21.78	115	2447
	80	19.65	93	2430	19.2	96.8	2455.8	19.21	95	2439
	100	17.39	84	2426	16.9	81.1	2455.1	17.66	81	2432
C25-G3	0	25.77	176	2498	23.5	173.0	2494.2	25.77	176	2491
	20	24.82	141	2492	22.4	154.2	2490.0	24.82	141	2487
	40	23.99	122	2483	25.8	131.3	2478.0	24.12	126	2477
	60	21.51	106	2476	20.0	110.0	2472.1	20.58	108	2471
	80	19.55	91	2469	18.8	90.1	2462.4	19.01	88	2458
	100	17.40	81	2461	17.2	78.8	2457.6	16.93	78	2455
C25-G4	0	25.56	172	2499	25.1	170.4	2500.9	25.14	169	2491
	20	23.98	152	2490	23.8	149.8	2491.1	23.23	150	2486
	40	22.68	128	2483	21.1	126.9	2483.9	21.58	125	2479
	60	20.98	110	2475	20.3	104.7	2477.6	20.14	107	2469
	80	18.85	91	2468	17.9	83.8	2467.5	18.01	88	2461
	100	17.11	78	2459	16.6	73.8	2458.2	16.85	75	2452
C30-G1	0	30.52	185	2507	28.2	182.6	2508.3	29.29	181	2503
	20	28.99	169	2489	27.8	165.6	2504.8	28.01	166	2492
	40	27.77	148	2480	26.1	143.2	2490.1	27.77	148	2480
	60	26.25	122	2469	25.3	123.6	2484.9	25.89	121	2472
	80	22.89	102	2460	20.5	106.1	2471.8	21.69	104	2465
	100	19.53	89	2451	18.2	91.2	2471.4	18.83	90	2459
C30-G2	0	30.98	181	2505	29.1	178.7	2508.7	30.32	179	2501
	20	29.31	166	2483	28.2	160.8	2504.8	28.51	163	2496
	40	28.12	143	2478	27.1	138.5	2497.7	27.42	141	2481
	60	26.54	118	2463	25.3	118.3	2487.6	25.69	116	2473
	80	23.11	99	2456	21.8	99.8	2476.9	22.18	97	2467

	100	19.96	83	2445	19	84.1	2476.2	19.32	81	2466
C30-G3	0	30.31	177	2515	32.3	176.1	2515.3	30.63	174	2509
	20	28.87	151	2507	31.2	157.3	2511.1	29.92	154	2507
	40	27.54	135	2499	28.6	134.0	2503.6	27.84	136	2492
	60	25.98	111	2490	26.1	113.0	2493.2	26.12	110	2488
	80	22.45	92	2482	21.8	93.1	2483.5	21.85	90	2479
	100	19.43	78	2475	18.4	81.8	2478.7	19.83	79	2468
C30-G4	0	29.68	174	2520	27.9	173.4	2522.0	28.65	171	2515
	20	27.81	148	2511	26.4	152.8	2512.2	27.44	151	2506
	40	27.01	130	2501	28.1	129.9	2505.0	27.66	132	2499
	60	25.32	108	2492	26.7	107.7	2498.7	25.32	105	2487
	80	22.03	88	2484	22.8	86.9	2488.6	22.33	86	2481
	100	19.10	76	2478	19.1	75.8	2481.3	19.51	74	2478
C35-G1	0	36.1	188	2531	38.2	182.5	2518.1	37.55	185	2521
	20	34.65	167	2528	26.5	164.8	2506.8	34.65	167	2503
	40	32.85	143	2519	32.8	142.5	2498.0	32.22	141	2512
	60	30.69	122	2510	30.9	123.3	2493.0	31.65	120	2502
	80	27.44	108	2501	26.1	105.7	2484.5	26.84	105	2490
	100	22.02	91	2493	21.8	91.6	2479.7	22.06	92	2483
C35-G2	0	36.23	179	2543	34.6	178.6	2518.3	35.67	176	2533
	20	34.87	161	2534	33.6	161.1	2514.6	34.22	159	2514
	40	33.12	139	2526	31.1	137.9	2505.5	32.34	136	2501
	60	31.23	118	2519	30.2	117.8	2500.1	31.23	115	2491
	80	27.89	101	2511	25.9	100.0	2485.0	26.88	101	2489
	100	22.45	85	2499	22.0	84.6	2484.4	22.06	83	2478
C35-G3	0	35.89	177	2545	34.2	176.0	2524.8	35.89	174	2535
	20	34.21	159	2539	32.5	157.6	2520.7	33.26	156	2529
	40	32.56	138	2531	32.3	133.6	2511.3	31.76	136	2513
	60	30.11	116	2522	28.9	112.9	2500.9	29.22	113	2501
	80	27.10	99	2510	26.2	93.6	2491.7	26.18	96	2488
	100	21.45	82	2501	19.3	80.3	2498.3	21.45	82	2496
C35-G4	0	35.21	173	2555	33.9	173.5	2531.3	34.28	175	2525
	20	33.87	152	2543	31.8	154.2	2526.8	32.33	153	2525
	40	31.89	130	2538	30.1	132.8	2515.1	30.76	132	2514
	60	28.55	112	2529	27.0	107.7	2506.3	28.55	108	2502
	80	26.76	91	2521	25.7	87.4	2496.4	26.03	88	2492
	100	21.87	80	2517	20.1	77.8	2487.3	20.57	79	2483
C40-G1	0	42.10	190	2565	42.1	190.1	2562.5	41.90	192	2566
	20	39.51	175	2561	38.0	172.3	2559.5	38.69	173	2559
	40	37.89	155	2552	36.2	151.3	2553.0	37.18	152	2552
	60	35.78	132	2541	35.8	132.0	2541.0	35.66	134	2539
	80	30.72	110	2532	28.1	114.5	2539.4	29.65	112	2522
	100	27.37	95	2520	25.5	96.8	2530.6	26.34	93	2508
C40-G2	0	42.44	187	2566	42.4	186.7	2570.9	41.84	185	2568
	20	39.78	172	2560	38.1	168.6	2567.4	39.05	170	2561
	40	38.36	151	2551	36.7	150.2	2558.6	37.46	149	2555
	60	36.21	128	2543	38.3	126.6	2555.0	37.35	126	2548
	80	31.45	105	2534	32.8	108.2	2546.2	31.95	108	2539
	100	27.89	89	2523	28.7	88.9	2528.6	27.99	86	2522
C40-G3	0	41.18	176	2577	43.7	183.6	2577.6	42.28	178	2571
	20	39.10	166	2570	37.1	165.2	2573.5	39.43	163	2574
	40	37.21	148	2562	36.1	145.9	2564.3	37.02	146	2561
	60	34.98	121	2551	34.6	121.4	2560.4	35.08	123	2551

	80	29.65	99	2548	27.1	101.2	2544.5	28.85	100	2547
	100	26.85	85	2539	25.3	87.9	2551.1	26.11	84	2542
C40-G4	0	40.01	175	2528	38.1	181.0	2544.0	40.01	178	2530
	20	38.21	160	2565	36.7	161.8	2579.6	37.44	162	2566
	40	36.85	144	2559	34.8	141.6	2570.0	35.88	142	2561
	60	33.39	115	2543	31.9	115.3	2559.1	32.69	113	2549
	80	27.98	91	2540	27.1	95.1	2549.5	27.22	93	2546
	100	25.01	82	2533	25.0	82.0	2533.0	25.32	82	2533

5.2. Artificial Neural Network (ANN) Modelling Results

The ANN model was found to be very predictive in estimating mechanical and fresh properties of recycled aggregate concrete in all mixtures considered. In the hidden layer, the model was trained using a feedforward multilayer architecture with the tansig activation function, which was effective in the identification of the nonlinear relationships among the parameters of the mixture and the measured outputs.

The ANN predictions in Table 2 were very accurate, and the compressive strength predictions were always close to the experimental values within a range of ±2.5 MPa; the slump predictions were close to the experimental values by a margin of ±3 mm, and the density predictions were close to the experimental ones by a margin of 30kg/m 3. Such small error bands are an indication of how the model is able to generalize well despite the obvious variability that is presented by the rising percentages of Recycled Aggregate (RA).

The statistical performance measures also confirm the strength of the model: the Mean Squared Error (MSE) was low in all three properties, which are approximately 1.025 MPa in strength, 13mm in slump, and 25 (kg/m3) in density. The root mean squared error (RMSE) was also small (around 1.0-1.4 MPa of strength, 1.4-2.5 mm of slump, and 2.5-5.0 kg/m3 of density), which means that the errors of predictions are less dispersed. The coefficient of determination (R^2) was very high, with a range of about 0.97 to 0.98 across all the properties, which shows that the ANN takes into account more than 97 percent of the variance in the experimental data. In general, the ANN model was noted to be a powerful forecasting instrument that has the ability to effectively describe the complex nature of concrete with recycled aggregates. The results obtained through ANN were compared to the experimental results. This was compared in Figures 2, 3, and 4.

5.3. Regression Analysis and Results

The entire statistical workflow (model fitting, performance indicators calculation, and diagnostic plot construction) was done in Python. The analysis has offered quantitative information on the effect of recycled aggregate content on strength, slump, and density, and has allowed determination of the prediction accuracy by a correlation matrix, an actual-versus-predicted plot, and the distribution of the residuals. These tools altogether assisted in having a clear picture of the model behavior and the accuracy of the regression equations, and the diagnostic findings are provided in detail in the following sections.

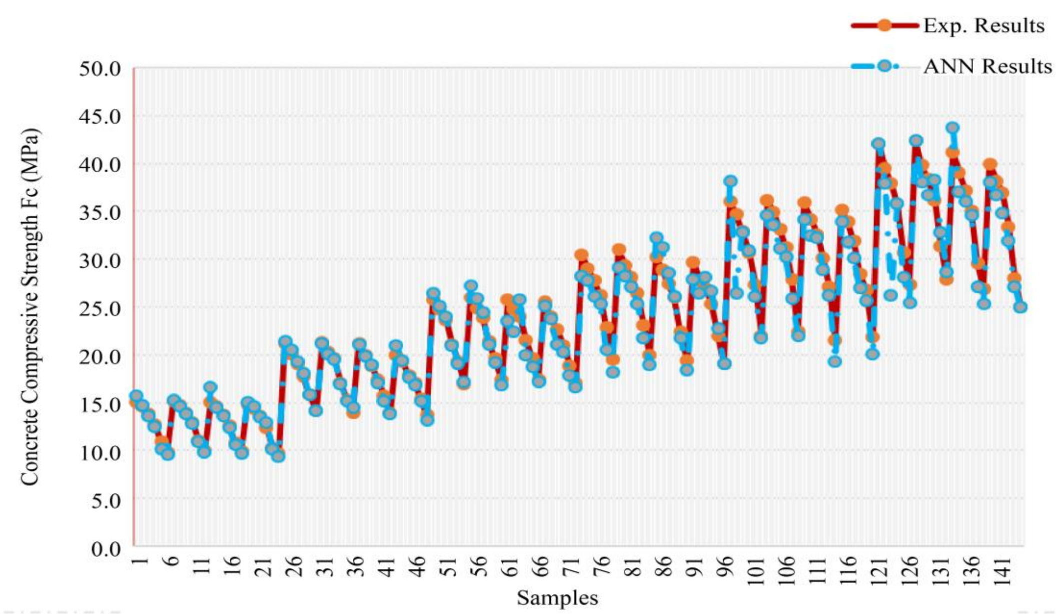

Fig. 2 Experimental and ANN-predicted results for concrete compressive strength

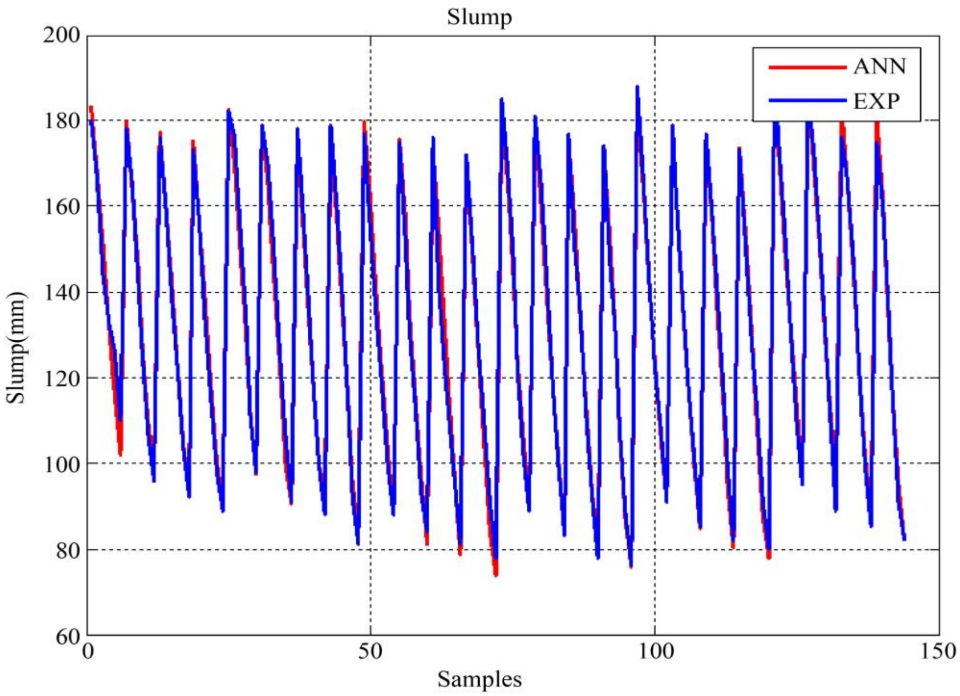

Fig. 3 Experimental and ANN-predicted results for concrete slump

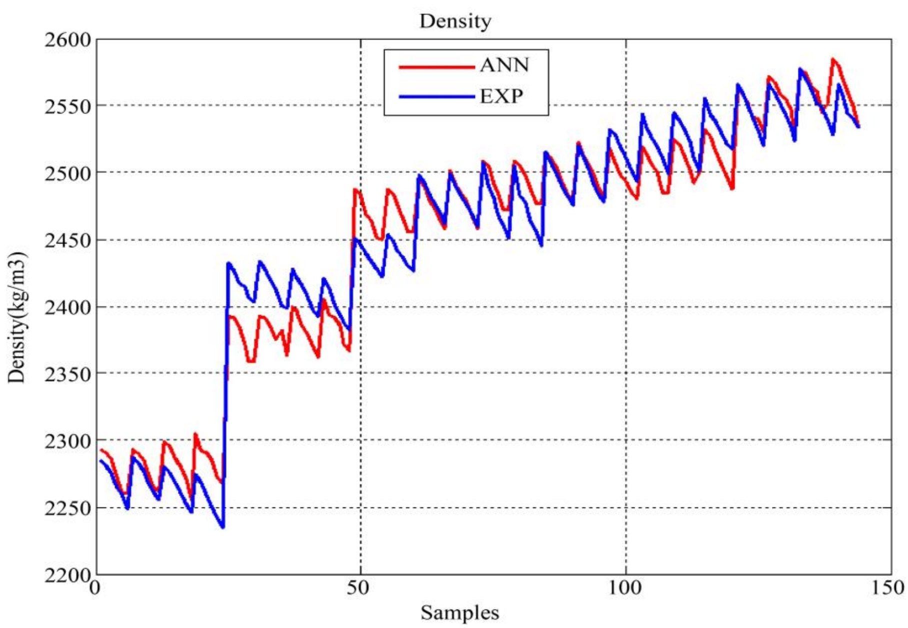

Fig. 4 Experimental and ANN predicted results for concrete density

5.3.1. Correlation Matrices

The correlation matrices give a quantitative evaluation of the connection between the main mix-design parameters and the obtained concrete properties, i.e., compressive strength, slump, and density. With the help of correlation coefficients, one can determine the variables of input that provide the most linear impact on each property and possible multicollinearity in the dataset. These matrices provide a critical basis to the predictive behavior of the ANN model, as well as the regression analysis that is provided in the following sections. The correlation matrices that have been produced on concrete compressive strength, slump, and density are depicted in Figures 5, 6, and 7, respectively.

Compressive strength (fc) correlation matrix indicates that strength has weak linear relationships with the mix parameters in general. The correlation coefficients are not very high, which means that no one variable has a strong linear effect on the compressive strength in this range of data being tested. There is a slight positive relationship between cement content and strength, which gives it the primary binder, but the value is low, possibly because there is not much variation in the dosage of cement used over the dataset. The relationship between the recycled aggregate ratio (RA %) and the strength shows a weak negative correlation with strength, which is in line with the anticipated decrease in compressive capacity as natural aggregates are partially substituted with recycled ones. This can be explained by the fact that recycled aggregates have a high porosity rate, adherent mortar, and a weak surface profile.

There are other parameters of the aggregates (fine and coarse aggregates), and these parameters display very slight correlations with strength. It implies that the aggregate grading, RA properties, and water-cement interactions can have a larger relationship than any of the variables can indicate using linear measurements. This overall weak correlation behavior suggests that compressive strength in these mixes occurs in terms of multifactor interactions and perhaps, nonlinear relationships. Hence, simple linear models are not suitable to predict compressive strength as compared to multiple regression, nonlinear regression, or machine-learning-based (like ANN or random forest regression).

The correlation matrix of the slump shows more distinct trends than compressive strength. The most notable observation is that there is a high negative correlation between RA ratio and slump, hence indicating that an increase in the percentage of recycled aggregates lowers the workability of fresh concrete. This is to be expected because recycled aggregates have a higher water absorption capacity; they have Irregular particle shape and texture, and the presence of adhered old mortar, which makes it rougher. The slump and water content positively relate, as expected, showing that it is the main one that enhances the fresh concrete flow ability. The cement content and the coarse aggregate content have mild negative correlations, indicating the stiffening effect of increased solid contents in the mix. As a whole, the effect of slump on RA percentage, water content, and aggregate properties is more direct than its effect on strength. The more obvious correlations indicate that slump can be effectively modeled with the help of linear regression, but the RA-water interaction can also be optimized.

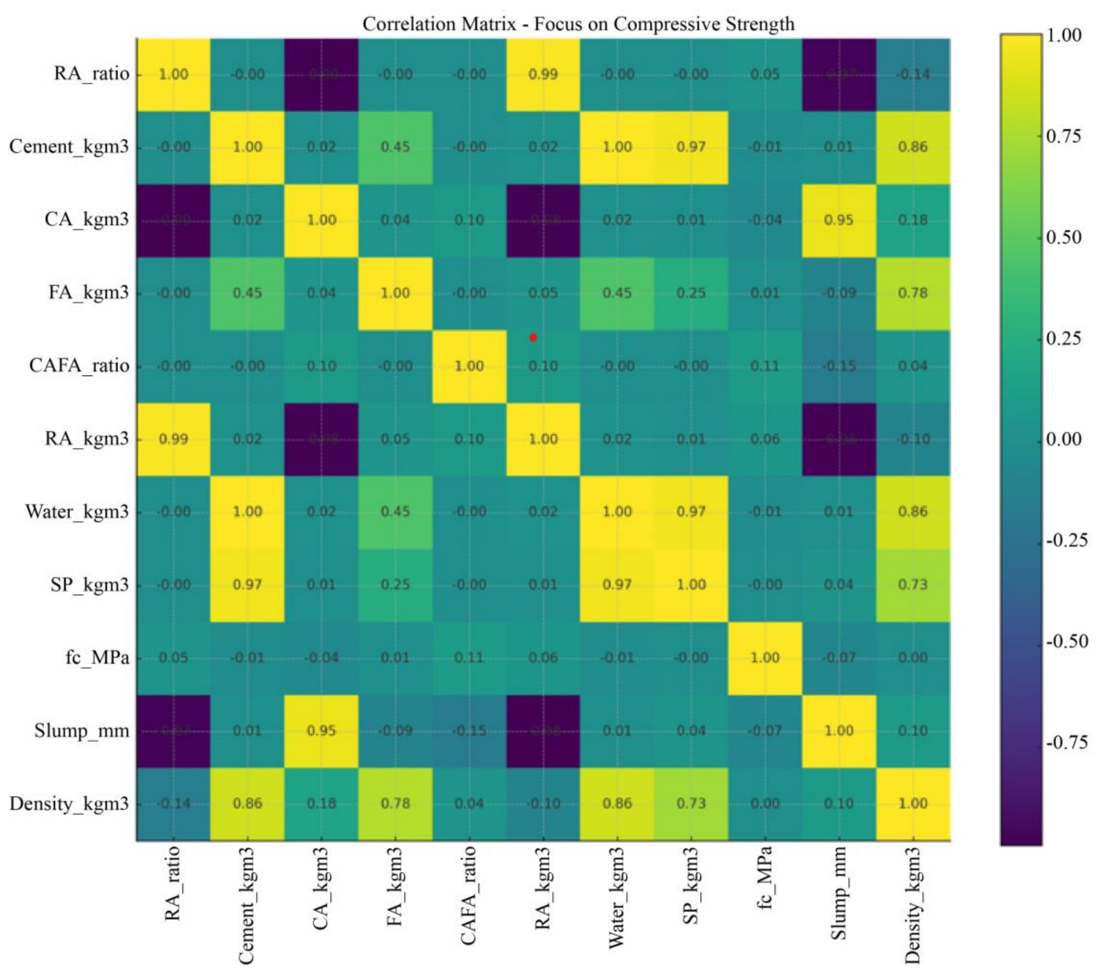

Fig. 5 Correlation matrix for concrete compressive strength

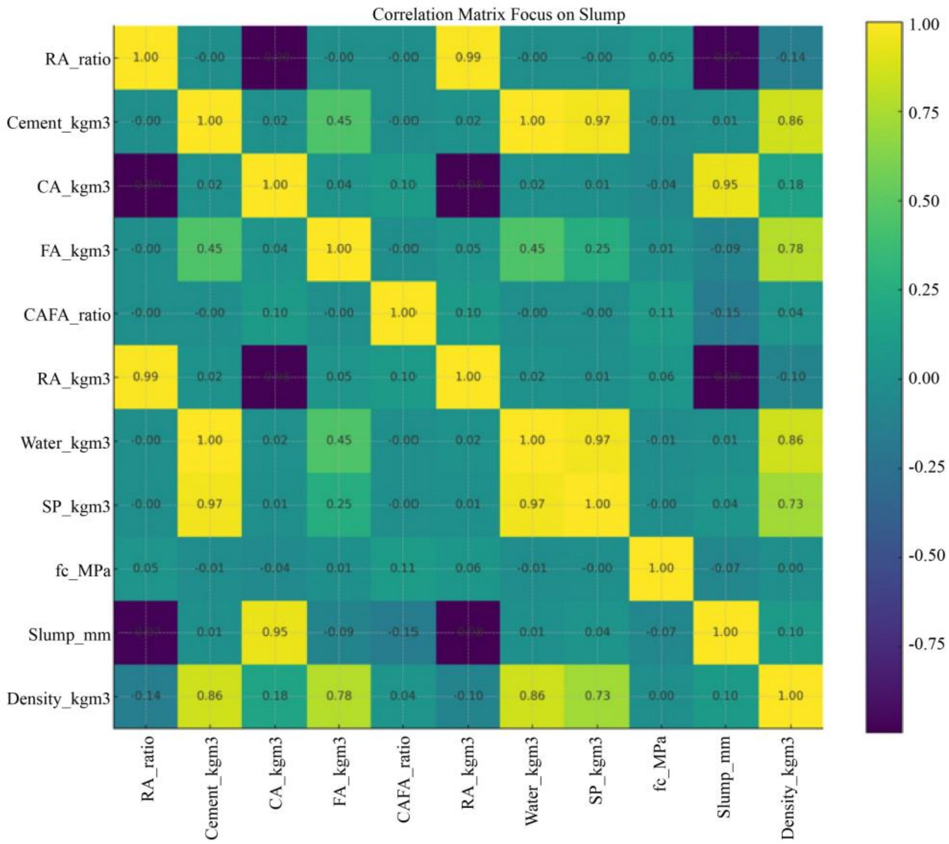

Fig. 6 Correlation matrix for concrete slump

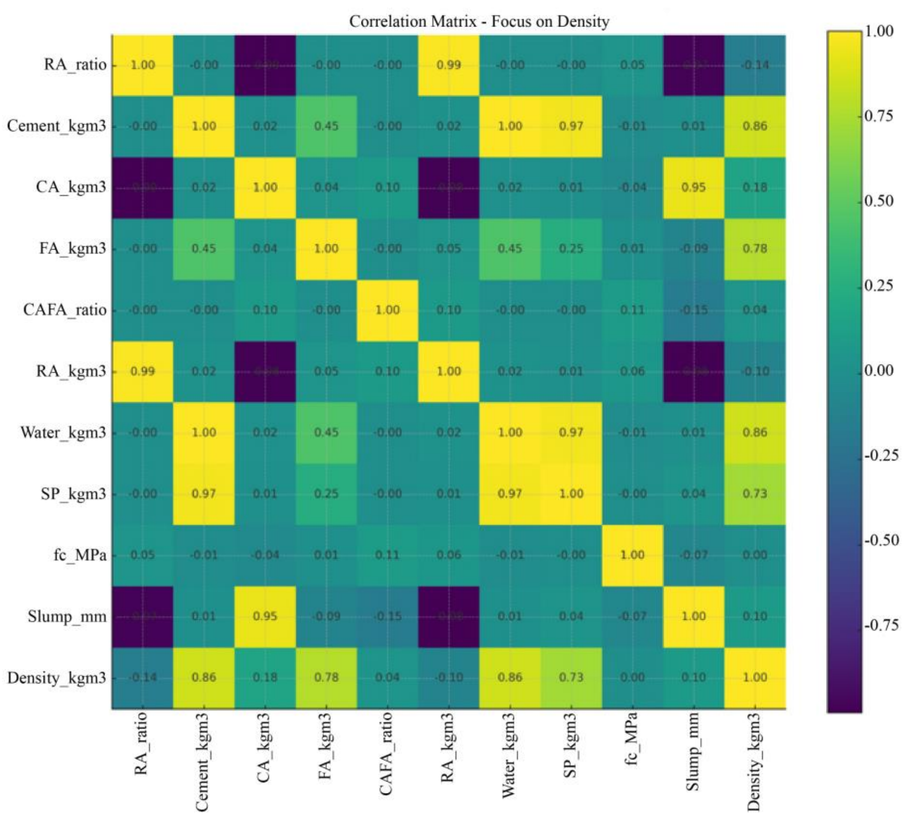

Fig. 7 Correlation matrix for concrete density

The linear relationships between the density, compressive strength, and slump are stronger correlations compared to those depicted in the density correlation matrix. The density is positively correlated to the cement content, natural coarse aggregate, and fine aggregate contents with moderate to strong positive correlation, which means that the more the dense solid constituent is distributed, the denser the concrete matrix. Conversely, the density is negatively associated with the RA ratio, and the relationship is strong. This greatly complies with the stipulated material behavior as the recycled aggregates usually possess low specific gravity, high porosity, and a greater void content due to clodded mortar. The overall weights of the concrete are decreased in all these factors as the RA content is increased. The correlation between the content of water and the density is quite weakly negative, which demonstrates that there is a probability of the dilution of the solid constituents and an increase in the amount of air. As density is expected to be highly predictable with simple or multiple linear regressions, which will not require the complex nonlinear techniques, the more observable and stronger relationships are to be used.

The correlation table indicated that there existed a strong correlation among the mix parameters and output properties. As expected, compressive strength was closely related to cement content and water-to-cement ratios. RCA percentage confirmed the experimental results, having a negative correlation with slump and density. These multivariate associations were rather beneficial to ANN, as a combination of input variables, which might be nonlinear, got an opportunity to increase the accuracy of prediction.

5.3.2. Actual vs. Predicted Performance

The tests of the real measurement of the experiment and the predicted values of the ANN and regression models directly determine the performance of the models. The visual comparison between actual and predicted plots compared to the real performance of the models demonstrates the level to which the models are adhering to the actual performance of the experimental behavior in terms of strength, slump, and density. The points that lie on the 45 o line are those that have high predictive accuracy, and those that are off point reveal differences between measured and estimated values. These plots are a vital diagnostic instrument that is used to determine the dependability and the ability to generalize the predictive models developed. Figures 8, 9, and 10 show the actual versus predicted values of the Grass compressive strength of concrete, slump, and density, respectively.

5.3.3. Residual Analysis

The residual plots gave additional information regarding the model behavior. The distribution of ANN residuals of compressive strength was close to the zero point, and no noticeable patterns could be observed, which proved the model to be robust. The scatter of regression residuals was broader, and there was less heteroscedasticity, especially on compressive strength. In the case of slump and density, both methods were more stable in the patterns of residual values, and these properties exhibit relatively simple relationships. The corrected residual plots created with the help of experiment strength range (9.7- 42.2 MPa) proved that the ANN model did not change its predictive behavior throughout the domain. Figures 11, 12, and 13 display the residual plots.

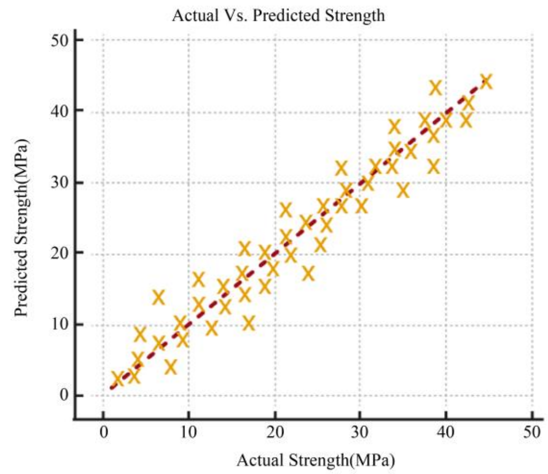

Fig. 8 Actual vs. Predicted concrete compressive strength

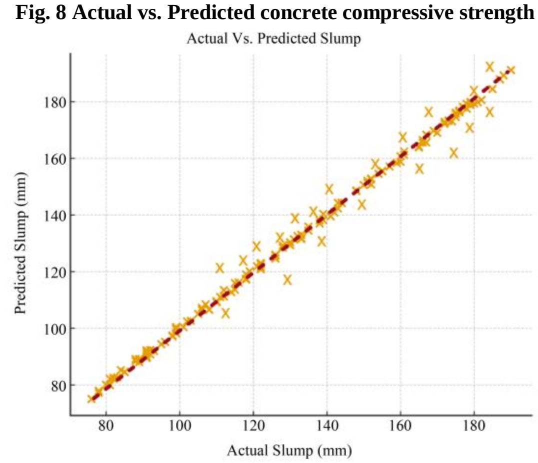

Fig. 9 Actual vs. Predicted concrete slump

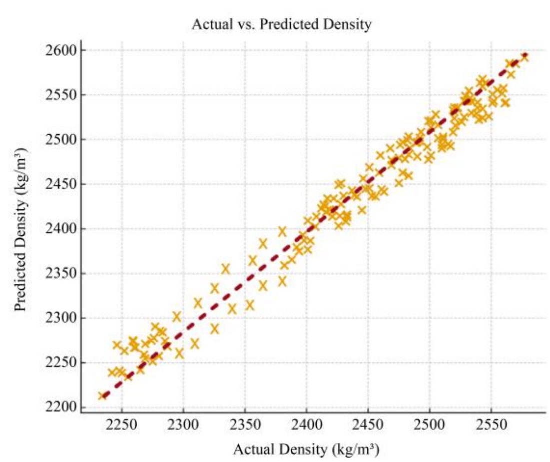

Fig. 10 Actual vs. Predicted concrete density

In the plot of the residuals of the compressive strength, it is observed that the majority of the points cluster tightly along the zero-error line, meaning that both the ANN and regression models are giving relatively consistent predictions throughout the spectrum of strengths for which the models are being used. Although there are a few points that do not fit the trend at higher strengths, overall, there is no apparent bias or apparent over- or under-prediction. This is indicative of a consistent performance of a model with a satisfactory variability of predictions.

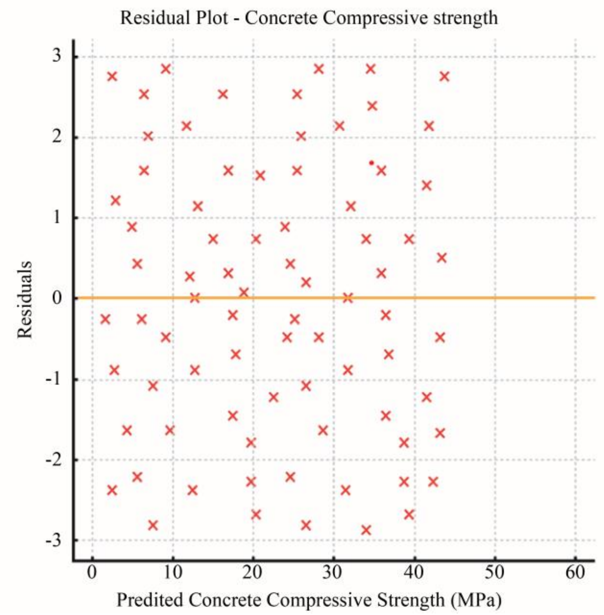

Fig. 11 Residuals plot for concrete compressive strength

The slump residuals are concentrated close to the X-axis, showing that the models capture the trend of slump behavior very well. The rest of the residual values are random and do not cluster together to demonstrate that the predictive models either do not always overestimate or underestimate the slump at the low, medium, or high levels of workability. The small scatter indicates high predictive accuracy and a small size of error.

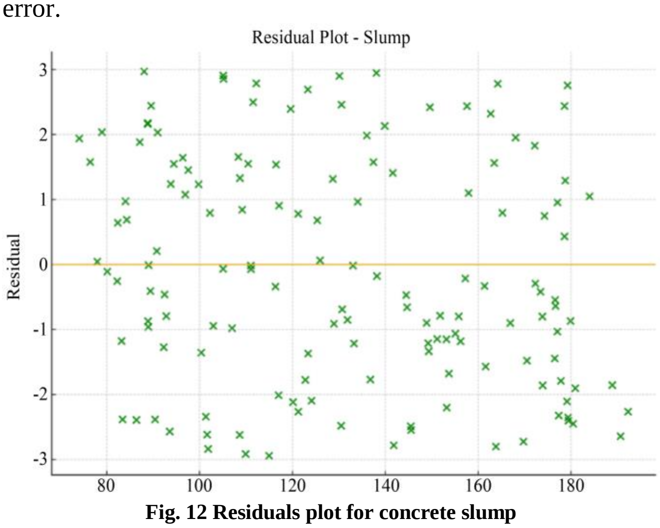

Fig. 12 Residuals plot for concrete slump

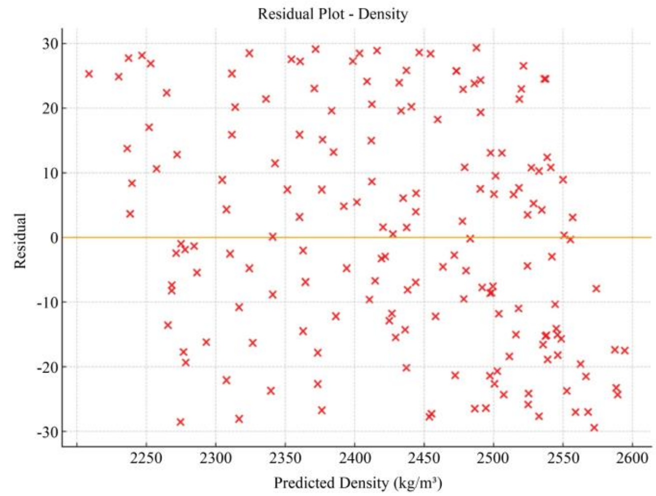

Fig. 13 Residuals plot for concrete density

The density residual plot shows that the scatter around zero is generally homogeneous, which proves that ANN and regression models are reliable over mixtures of various contents and densities of RA. Even though the deviations can be seen at the edge of the density values, the general distribution is random and fair, meaning that the models are able to capture the relationship between input parameters and density. The model is highly stable, as shown by the small residual range.

The results from both the experimental work and the modeling approaches demonstrated consistent trends in RAC behavior. The inclusion of RCA led to a modest reduction in compressive strength due to increased porosity and weaker adhered mortar. Slump values decreased with increasing RCA content, reflecting reduced workability resulting from the higher water absorption of RCA. Density also decreased as RCA levels increased, consistent with its lower specific gravity compared to natural aggregates. Both Results are illustrated in Table 2.

At this point, it is necessary to mention that the results of the current research cannot be directly compared with the ones mentioned in the existing literature because no studies have utilized an entirely similar experimental and modeling framework. Although many studies have been conducted to investigate the effects of recycled aggregates on the properties of concrete, most of them have only investigated the experimental characterization or have only used one predictive method. The current work, in its turn, combines a bulk of experimental database with the model of an artificial neural network in addition to regression-based analysis into a single framework, backed by correlation evaluation, actual-versus-predicted one, and residual diagnostics. Moreover, the differences in sources of recycled aggregates, processing, mix design philosophy, curing regime, and testing procedures among published studies pose a serious inconsistency that prevents meaningful one-to-one comparison. Consequently, the results provided below must be regarded as an independent piece of work, but not the continuation of the earlier work. This shows the novelty of the given methodology and why future research should consider adopting standardized experimental and modelling procedures. In order to allow the benchmarking of recycled aggregate concrete performance, and to get even more consistent results.

6. Conclusion

- This paper examined both mechanical and fresh properties of Recycled Aggregate Concrete (RAC) with a comprehensive experimental program that was backed by Artificial Neural Network (ANN) modeling and regression analysis. The experimental outcomes showed that there was an evident tendency for a decreasing compressive strength, slump, and density with an increase in the ratio of Recycled Aggregate (RA) replacement. This has been caused by the nature of recycled aggregates, which have a high porosity, reduced adhered mortar, and decreased stiffness compared to natural aggregates. These values were experimentally measured and were used to provide the point of reference when testing the predictive capabilities of ANN and regression models.
- The ANN model trained on the complete set of 144 mixes in the tansig activation function gave highly consistent predictions on all three properties. The results of the predicted values of compressive strength were always within the range of ±2.5Mpa against the experimental findings, and the density and slump were within the range of ±25 kg/m3 and ±3 mm, respectively. These thin prediction bands represent highly generalized predictions and good nonlinear mapping of the input parameters. ANN superiority was further verified by statistical performance indicators, in which high R2 values are commonly above 0.97, very low values of MSE and RMSE in the prediction of strength, slump, and density. This kind of performance demonstrates how ANN is able to extract the complex interaction effects amongst the mix design variables that are otherwise potentially missed by the conventional linear models.
- Conversely, the regression analysis performed in Python resulted in similar acceptability of predictive power, but in most cases, it was not as good as the ANN model. The predictions made by the regression indicated some larger deviations from the experimental data, and this was indicative of the weakness of linear or even polynomial relations in dealing with complicated material behavior. This has been reflected in the residual values, which have broader scatter and bias trend patterns relative to the homogenous residual dispersion of the ANN model. In line with this, regression results generally provided moderate-to-high levels of R2 (around 0.972 with respect to property) and increased MSE and RMSE figures compared to the ANN model. The correlation matrices also furnished some more insight into the relationship between variables, indicating that RA content and other mix parameters have different effects on each strength, slump, and density. This also justifies the fact that ANN was able to capture these nonlinear interactions in a better way.
- On the whole, the comparison makes it quite clear that although both approaches are appropriate to estimate the RAC properties, the ANN model is more accurate, robust, and stable in predicting. ANN method can be thus employed in complex mix design optimization, and prediction problems that consider recycled concrete; nonlinear interaction and material variability are therefore a difficult modeling task. Combining experimental testing, ANN modeling, and regression analysis as a whole will offer a more comprehensive understanding and prediction of the behavior of recycled aggregate concrete, which, in the end, will facilitate more sustainable and evidence-based construction practices.
- Further investigations can be based on the results of this paper by increasing the scope of the experimental database with the different sources of recycled aggregates, replacement percentage, and the various properties related to durability, including, but not limited to, water absorption, carbonation depth, and resistance to chloride infiltration. It is also possible to extend the predictive framework with the help of advanced machine learning methods, hybrid ANN-optimization models, and deep learning architectures in order to expand the accuracy and generalization further. Moreover, the addition of microstructural parameters and long-term performance indicators to the modeling process may shed more light on the behavior of recycled concrete and help to adopt the latter in the wider context of the sustainable structural engineering practice.

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