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Predicting the Influence of Superplasticizer on the Mechanical Properties of Rice Husk Ash-Based Self-Compacting Concrete (RHA-SCC)

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Abstract: *This study examines superplasticizer dosage effects on properties of self-compacting concrete (SCC) containing rice husk ash (RHA) as 10% cement replacement. The study aimed to determine optimal superplasticizer dosage and develop a predictive model for strength properties. Tests were conducted on M30 and M40 grade concrete with superplasticizer dosages (0.6% to 2.0%). Fresh properties were evaluated using slump flow, L-box, and sieve tests. Hardened properties were assessed through compressive and splitting tensile strength tests at different curing ages (7, 28, 56, and 90 days). Results showed an optimal superplasticizer dosage was 1.3% for both grades, with excessive dosages decreasing strength. Regression analysis developed predictive models considering curing age and superplasticizer dosage. The models showed high accuracy, with R^2 values of 0.9886 and 0.945 for compressive strength, and 0.955 and 0.8556 for splitting tensile strength of M30 and M40 concrete respectively. The findings demonstrate RHA's potential as a sustainable cement alternative in SCC production.*

Keywords: self-compacting concrete; Compressive strength; Splitting Tensile strength;

1. INTRODUCTION

Concrete is a widely used construction material made from cement, aggregates, water, and sometimes addition and admixtures with each component contributing to its strength. To improve efficiency and performance, variants like Self-Compacting Concrete (SCC) which was first developed in Japan in the mid-1980s have been utilized. SCC uses the same basic mix as traditional concrete but includes an Admixture known as superplasticizer to allow it to flow and settle without the need for vibration[1]. The essence of super-plasticizer is to reduce the water/cement ratio and enables the concrete to easily fill intricate formwork, particularly in sections with dense reinforcement. It enhances overall workability, reduces bleeding in fresh concrete, and minimizes the risk of drying shrinkage, thereby contributing to higher compressive strength compared to vibrated concrete[2]. Also, It is highly versatile, suitable for both precast and on-site construction, and can be delivered via batching plants, ready-mix trucks, pumps, or manual pouring [3]

Due to the high cement content in self-compacting concrete (SCC), and considering that the cement industry produces approximately 1.8 gigatons of CO_2 annually, contributing around 7–8% of global carbon emissions which leads to a significant environmental concern [4]. To address these environmental concerns, SCC can be effectively combined with supplementary cementitious materials such as fly ash, blast furnace slag, and rice husk ash (RHA).

Rice husk ash (RHA), an agricultural byproduct of one of the world's most important staple crops[5], is produced in large quantities around 70 million tons annually by rice-growing countries. It can serve as a stabilizing agent for materials like soil by influencing their volume change behavior [6] and can also be used as a partial substitute for cement in construction applications [7]. In Nigeria alone, about 2 million tons of rice husk are generated each year, with around 20 kg of husk produced for every 100 kg of rice processed[8], When burned, rice husk yields about 25% ash, which contains 85–90% amorphous silica and approximately 5% alumina, giving it strong pozzolanic properties [9], [10]. The chemical composition of RHA by various researchers are illustrated in Table 1. it shows that silica content and presence of minor oxides (such as alkalis, sulfate, and calcium oxide) in the RHA samples indicate strong pozzolanic properties, which can enhance concrete strength, improve durability, and lower material costs. Hence, Utilizing RHA in concrete does not only lowers the carbon footprint of cement production but also supports the sustainable reuse of agricultural waste [11].

Table 1: Oxide Composition of Rice Husk Ash

Chemical Constituents (Oxides)	Usman, et. *al.* (2014) [12]	Said *et. al.,* (2017) [3]	Adinna *et. al.,* (2019) [13]
SiO_2	97.10	77.19	88.32
Al_2O_3	1.14	6.19	0.46
Fe_2O_3	0.32	3.65	0.67
CaO	0..07	2.88	0.67
MgO	0.83	1.455	0.44
SO_3	0.15	-	-
MnO	-	0.135	-
Na_2O	0.09	-	0.21
K_2O	0.18	1.815	2.91
P_2O_5	-	1.107	-
LOI	0.97	5.429	5.81
SAF	98.56	87.03	89.45

Studies have demonstrated that incorporating rice husk ash (RHA) as a partial cement replacement can improve both the fresh and hardened properties of self-compacting concrete (SCC). Research by [14], [10], [15], [16] showed that a 10% RHA replacement significantly enhanced compressive strength, with up to 20% replacement being effective without negatively affecting performance Similarly, [3] and [9] found that mixes containing 10% RHA combined with 4% superplasticizer achieved the highest strength. However, increasing RHA content beyond 20% led to excessive water absorption, reduced workability, and resulted in SCC that crumbled easily [14] [9].

Additionally, it is important to note that SCC is inherently complex due to the precise balance of its constituent materials, which are necessary to achieve both adequate flowability and mechanical strength. Its performance is influenced not only by the water-cement ratio but also by the type and content of other ingredients, making the mix design process both time-consuming and costly[17].To accelerate SCC production and reduce reliance on trial-and-error methods, predictive modeling approach are often used by different researchers for time saving and estimating concrete strength efficiently[18] one the approach Regression model techniques, which are a combination of both linear term and quadratic terms widely used to predict the strength of various types of concrete[19] [20]

Numerous studies have been conducted to predict concrete strength and enhance its sustainability. Maina et al. (2019) applied a Multi-Linear Regression model to predict the compressive strength of concrete using variables such as the water-cement ratio, mix design quantities, and the physical and chemical properties of fine aggregates [19]. The model was validated with independent samples, showing strong agreement between predicted and experimental results, which is consistent with the findings of [21]. Similarly, Dhiviya (2017) employed both Regression Analysis (RA) and Artificial Neural Networks (ANN) to develop predictive models for the fresh and hardened properties of self-compacting concrete (SCC) containing fly Ash using data collected from literature[22]. Also, study [8] predicted the strength of SCC made with a blend of fly ash and rice husk ash using the Adaptive Neuro-Fuzzy Inference System (ANFIS). The findings highlighted the suitability of such models for handling complex prediction problems while significantly reducing computational effort[17].

Further studies also explored the strength of RHA-based concrete which were limited to the prediction of traditionally vibrated concrete, such as the work conducted by [23] who focused on predicting concrete strength with Support Vector Regression (SVR) combined with three optimization algorithms: Firefly Algorithm (FA), Particle Swarm Optimization (PSO), and Grey Wolf Optimization (GWO). Among all models tested, the FA-SVR hybrid demonstrated the highest prediction accuracy. in the same vein, Chuanqi Li e*t al.* (2023) introduced a novel hybrid artificial neural network (ANN) model, optimized using the Reptile Search Algorithm with Circle Mapping (CMRSA), for predicting the compressive strength of RHA-based concrete. When compared with five other models, the CMRSA–ANN model achieved the highest prediction accuracy [15].

Additionally, Sobuz *et. al.,* (2022) investigated the rheological and mechanical properties of self-compacting concrete (SCC) reinforced with waste galvanized copper wire fiber and partially replaced with 2% rice husk ash (RHA). Their findings identified a mix containing 2% RHA and 0.75% copper fiber as delivering optimal performance compared to plain SCC [24]. Similarly, Mahmood *et al.* (2023) explored the use of Machine Learning (ML) and Deep Learning (DL) techniques to predict the performance of SCC containing varying proportions of RHA and Marble Powder (MP) as partial replacements for cement and filler [18]. Despite offering valuable insights into SCC Strength, their studies did not consider the effect of admixtures or superplasticizers on concrete strength.

Based on the gap existing in the literature, this research addresses key challenges in self-compacting concrete (SCC) by focusing on sustainability, strength optimization, and predictive modelling. It aims to enhance SCC production by using rice husk ash (RHA) as a partial cement replacement, determining the optimal superplasticizer dosage for improved mechanical strength, and develop a predictive model to estimate concrete strength, thereby reducing trial mixes, cost, and time. The study also emphasizes proper dosage practices to prevent issues like segregation and delayed setting, ultimately promoting SCC adoption in developing countries through improved performance and environmental benefits.

2. MATERIALS

This study employed Ordinary Portland Cement (OPC), coarse aggregate, fine aggregate, water, superplasticizer, and Rice Husk Ash (RHA) as a supplementary cementitious material.

2.1. Powder

The binder consisted of OPC with a 10% replacement by RHA, based on literature identifying this ratio as the optimal percentage. The OPC used was 3X-Dangote brand, grade 42.5N, with a specific gravity of 3.12 as determined by testing. Rice husks were processed by air-drying and subsequently burned in a kiln at a controlled temperature of 600°C for approximately two hours to produce ash. The resulting RHA was then cooled and sieved through a 75 µm BS sieve to obtain a fine powder. The consistency test on Cement + 10% RHA is obtained to be 33mm penetration while the initial and setting time is 69min and 216min respectively.

X-ray fluorescence (XRF), a non-destructive analytical technique capable of detecting elements from beryllium to uranium across a wide concentration range is used to determine the oxide composition of both the Cement and RHA as shown in Table 2.

Table 2: Summary of Oxide composition of OPC and RHA

OXIDE	Percentage composition (%)	
	CEMENT	RHA
SiO_2	15.614	82.171
Al_2O_3	3.222	0.403
Fe_2O_3	2.342	I.680
CaO	74.088	5.518
MgO	-	1.331

SO_3	1.48	2.9
TiO2	-	0.164
K_2O	-	1.89
MnO	0.045	0.345
NiO	-	-
LOI	3.13	4.47

$SAF = SiO_2 + Al_2O_3 + Fe_2O_3$

The combined content of SiO_2, Al_2O_3, and Fe_2O_3 (SAF) exceeded 75% in all samples—meeting ASTM C618:2003 requirements for pozzolans, With SiO_2 content above 70% and loss on ignition below 6%, RHA is classified as a Class N pozzolan [25] [26] or as Class F fly ash according to ASTM C618 (2008) [27], indicating strong pozzolanic properties.

2.2. Aggregate

Crushed granite with a nominal size of 20 mm was used as the coarse aggregate, with a specific gravity of 2.78 and a bulk density of 1587.87 kg/m³, shown in Table 2, naturally occurring clean river sand served as the fine aggregate, with a specific gravity of 2.62 and a fineness modulus of 2.77. The sieve analysis test of both fine and coarse aggregates are Sieve analysis was conducted in accordance with BS 812 (1985) and illustrated in Fig. 1, which signifies that there is more medium sand than fine and coarse sand and it is cohesion less while coarse aggregate particle size distribution indicates that the predominant size is 20mm, which is desirable for making concrete and both are is within EFNARC 2002 specification.

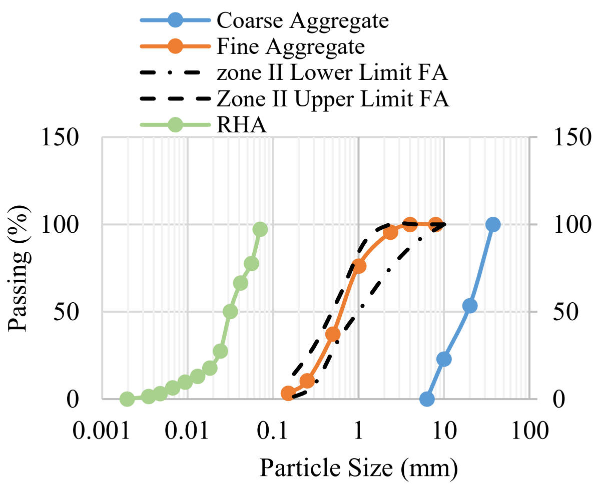

Fig. 1: Particle size distribution chart of RHA, fine and coarse aggregates

2.3. Admixture

The superplasticizer used was Conplast SP432-MS, a chloride-free admixture based on selected sulphonated naphthalene polymers. It is a brown liquid that disperses readily in water. According to the manufacturer, the recommended dosage ranges from 0.6 to 2.0 liters per 100 kg of cementitious material, with a specific gravity of 1.19.

2.4. Mixing

The mixing and curing water were potable tap water sourced from the Civil Engineering Laboratory at the University of Ilorin, Nigeria. Being fit for drinking, the water met the requirements of ASTM C1602-12, ensuring no adverse effects on concrete properties such as strength and durability.

3.0. METHOD

3.1. Mix Design of RHA-SCC

The mix design for M30 and M40 grade of RHA-SCC was developed based on ACI 211.1-91 [28] and EFNARC (2005) [29] guidelines. The Superplasticizer (SP) dosages were varied according to the manufacturer's recommended range of 0.6 to 2.0 liters per 100 kg of binder (cement + RHA), with specific dosages set at 0.6, 0.95, 1.3, 1.65, and 2.0 liters.it is important to note that to determine the effect of SP on SCC, all materials are kept constant while on SP dosage are varied. The detailed mix proportions for M30 and M40 concrete are shown in Tables 3 and Table 5 respectively. A total of 144nos of cube and 144nos of cylindrical specimen were cast for compressive strength and splitting tensile strength of concrete. The cube and cylinder samples were demolded after 24 hours and immersed in water tank for different curing age at 7days, 28days, 56days and 90days respectively as age (days) is also, an important variable in predicting concrete strength[30].

Table 3: Mix proportion of SCC of M30 grade

1	2	3	4	5	6	7
0	0	851	889	205	369	41
0.6	2.46	851	889	205	369	41
0.95	3.89	851	889	205	369	41
1.3	5.33	851	889	205	369	41
1.65	6.77	851	889	205	369	41
2.0	8.2	851	889	205	369	41

Table 4: Mix proportion of SCC of M40 grade

1	2	3	4	5	6	7
0	0	834	889	190	398	44.2
0.6	2.7	834	889	190	398	44.2
0.95	4.2	834	889	190	398	44.2
1.3	5.7	834	889	190	398	44

1.65	7.3	834	889	190	398	44.2
2.0	8.84	834	889	190	398	44.2

Note: 1= %SP (litres); 2= Dosage of SP (litres/m^3); 3= Coarse aggregate (Kg/m^3); 4= Water (Kg/m^3); 5= Cement (Kg/m^3); 7= RHA (Kg/m^3)

3.2. Workability test

The workability test such as filling ability (slump flow test), passing ability (L-box test) and segregation resistance (sieve test) was obtained based on the Preferred test method(s) for fresh properties SCC According to EFNARC 2002 and 2005.

3.3. Mechanical strength test

The compressive strength test, conducted as per BS EN 12390-3 (2009) [31] calculated using equation (1), used 144 cube specimens with varying SP dosages (0% to 2.0%) for M30 and M40 concrete, tested at 7, 28, 56, and 90 days of water curing. Similarly, the splitting tensile strength test, following BS EN 12390-6 (2009) [32] calculated using equation (2), used 144 cylindrical specimens tested at the same curing intervals, with both tests averaging results from three samples per mix and using a BUDENBERG 1560 kN capacity manual machine to determine strength at failure.

$$\text{Compessive Strength} = \frac{\text{Load}}{\text{Area}} = \frac{\text{Load(N)}}{0.10*0.10\ (\text{mm}^2)} \quad (1)$$

$$\text{Split tensile strength} = \frac{2\text{P (N)}}{\pi\text{DL}\ (\text{mm}^2)} \quad (2)$$

3.4. Mathematical Model of RHA-SCC

The model development for predicting compressive and splitting tensile strength of SCC (grades M30 and M40) involved several key stages. First, relevant experimental data such as mix proportions and strength values at different curing ages were collected. These data were then organized in Excel and normalized using the mean and standard deviation to improve model accuracy.

Model equations were generated using regression analysis in MATLAB R2007b, leveraging tools like simple and multiple linear regression. To evaluate the model's performance, several goodness of fit (GOF) metrics were applied: Root Mean Square Error (RMSE) to assess prediction accuracy, Sum of Squares of Error (SSE) to measure modelling error variation, Correlation Coefficient (R^2) to gauge the strength of the fit, and Adjusted R^2 to determine the significance of additional predictors.

4.0. Result and Discussion.

4.1. Fresh Properties Result

After testing the physical properties of the constituent materials, fresh property and mechanical strength tests were conducted to determine the optimal superplasticizer (SP) dosage, followed by predictive modelling. The summary of the fresh property test; Filling ability, passing ability and segregation resistance is presented in illustrated in Fig. 2,3 and 4 and it depicts that all the three workability properties of fresh SCC with different dosage of SP are satisfied at 1.3% and 1.65% for both grade of concrete as stated within the requirement of EFNARC 2005 guidelines. Hence, self-compatibility of the concrete has been achieved.

The slump flow results in Fig. 2 showed that increasing SP dosage led to higher slump values, with 2.0% exceeding the EFNARC (2002) limit of 650–800 mm, while 1.3% and 1.65% provided satisfactory flow for both M30 and M40 grades; lower dosages like 0.6% and 0.95% resulted in insufficient slump as found to be below the EFNARC (2002) limit, aligning with findings by [18]. Similarly, The L-box test results, shown in Fig. 3, reveal that the blocking ratio of SCC increases with higher superplasticizer (SP) dosages. Mixes with 1.3% to 2.0% SP demonstrated satisfactory passing ability within the EFNARC (2002) range of 0.8–1.0, with 2.0% SP showing the best performance achieving blocking ratios of 0.95 and 0.97 for M30 and M40, respectively.

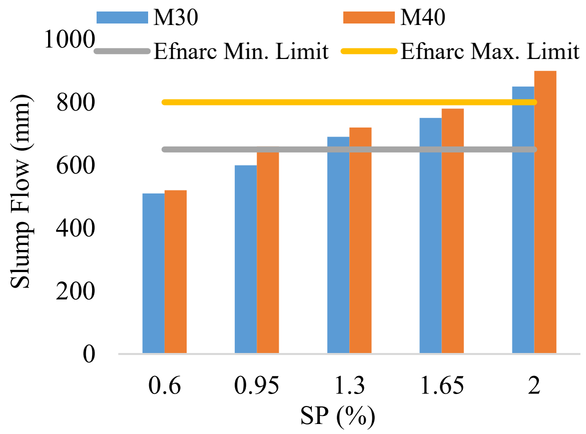

Fig. 2. Slump flow of M30 and M40 grade of concrete

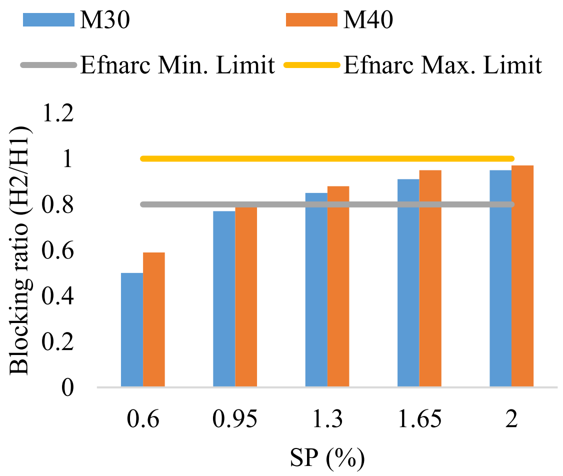

Fig. 3. Blocking ratio of M30 and M40 grade of Concrete

The segregation resistance results, shown in Fig. 4, indicate that stability improves with increasing SP dosage, with satisfactory values observed between 0.6% and 1.65% for both concrete grades falling within the EFNARC (2002) limit of 0–15%. However, at 2.0% SP dosage, the mix exceeded this limit, suggesting that excessive SP increases consistency and makes the mix more prone to segregation.

Fig. 4. Segregation resistance of M30 and M40 grade of

4.2. Mechanical Properties

The compressive strength development and Splitting Tensile Strength for M30 and M40 concrete, both control and SCC mixes illustrated in Fig. 5 and 6 respectively.

Compressive Strength:

The observed increase in compressive strength for both concrete grades follow a similar trend with the addition of superplasticizer (SP), attributed to its ability to enhance workability, allowing the concrete to flow more easily and fill molds more uniformly, thereby reducing voids and improving overall strength. Additionally, SP disperses cement particles, releasing previously entrapped water within cement clusters, which then becomes available for mixing and further enhances the hydration process[33]. However, the decrease in strength observed at 2.0% SP for M30 and at 1.65% and 2.0% SP for M40 may be attributed to delayed hydration and bleeding, resulting from excessive deflocculation of cement particles caused by high SP dosage. This observation is consistent with the findings reported by [16] and [34]

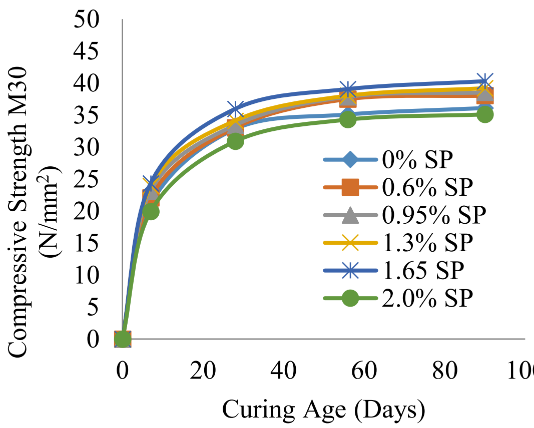

Fig. 5. Compressive Strength Development with SP% at curing ages for M30.

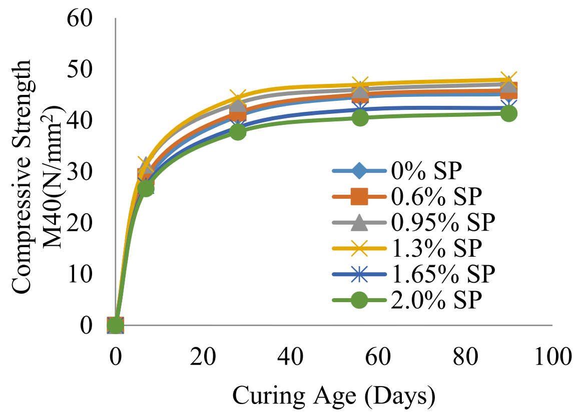

Fig. 6. Compressive Strength Development with SP% at curing ages for M40.

Splitting Tensile Strength:

The summary of splitting tensile strength of SCC for M30 and M40 are presented in Fig. 7 and 8, It is visible that the splitting tensile strength increases as the SP dosage increases and decreases with further increase which is similar with the result obtained in compressive strength.

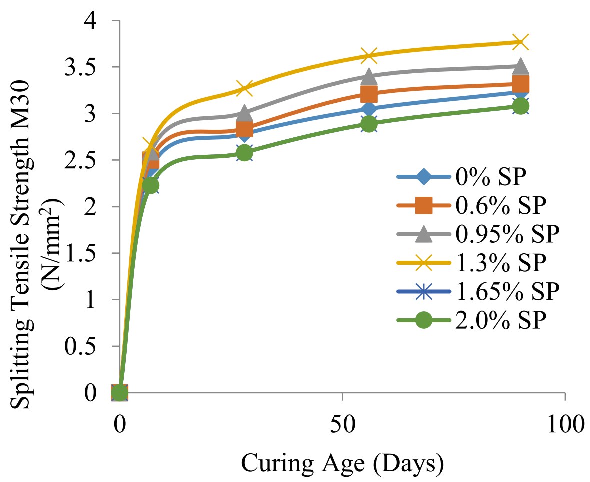

Fig. 7. Splitting tensile Strength Development with SP% at curing ages for M30.

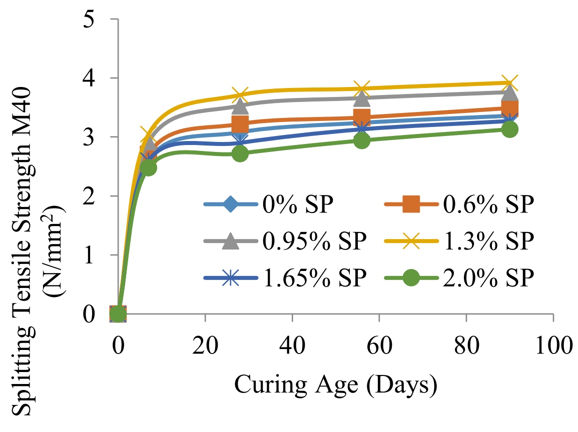

Fig. 8. Splitting tensile Strength Development with SP% at curing ages for M40.

4.3. Mathematical Model

The coefficients of the equations developed for predicting the compressive and splitting tensile strengths

of M30 and M40 concrete reflect the influence of various mix constituents on strength performance. These coefficients were obtained through regression analysis using MATLAB software. Due to the non-linear relationship between the dependent (strength) and independent variables, a combination of linear and quadratic terms was employed, as suggested by [20].
The primary independent variables curing age (X) and superplasticizer dosage (Y) were normalized to improve model accuracy. For M30, the normalization was based on a mean of 45.25 and 4.442, and a standard deviation of 31.8 and 2.77; for M40, the mean values were 45.25 and 4.787, with standard deviations of 31.8 and 2.927, respectively. The resulting response models for compressive strength (CS) and splitting tensile strength (TS) of concrete grades M30 and M40 are presented in Equations (3), (4), (5), and (6).

$$CS30 = f(t, sp) = 37.99 + 2.734T + 2.163SP - 4.649T^2 - 0.01186SP.T - 1.835SP^2 + 2.481T^3 + 0.05452T^2SP - 0.163SP^2T - 1.347SP^3 . \quad (3)$$

$$TS30 = f(t, sp) = 2.525 + 0.02766T - 0.3137SP - 0.0003012T^2 + 0.001821SP.T + 0.1413SP^2 + 0.00001245T^3 - 0.000008015T^2SP - 0.00009673SP^2T - 0.01317SP^3. \quad (4)$$

$$CS40 = f(t, sp) = 23.97 + 0.7336T + 3.567SP - 0.007754T^2 - 0.02115SP.T + 0.7427SP^2 \; 0.00002537T^3 + 0.0001222T^2SP - 0.002161SP^2T - 1.503SP^3 \quad (5)$$

$$TS40 = f(t, sp) = 2.416 + 0.02708T + 0.304SP - 0.0002511T^2 - 0.0007154SP.T + 0.3939SP^2 + 0.0000007384T^3 + 0.00007348T^2SP - 0.0002205SP^2T - 0.3028SP^3 \quad (6)$$

Where T= Time
SP= Super plasticizer

4.4. Model Validation
The developed model was validated for adequacy and accuracy using statistical metrics such as the Sum of Squared Estimate Errors (SSE), Coefficient of Determination (R^2), Adjusted R^2, and Root Mean Square Error (RMSE), as shown in Table 5 for compressive strength and splitting tensile strength. The results indicate a strong correlation, with low SSE and RMSE values reflecting a good model fit. The R^2 and Adjusted R^2 values, which represent the proportion of variance in the experimental data explained by the model, were 0.9886 and 0.9812 for M30, and 0.945 and 0.926 for M40 compressive strength, respectively. For splitting tensile strength, the values were 0.955 and 0.9261 for M30, and 0.8451 and 0.7914 for M40. These results demonstrate strong agreement between predicted and experimental strengths, confirming the model's high predictive accuracy. This aligns with findings reported by [35]and [36]

Table 5: Compressive strength and splitting tensile strength goodness of fit

Goodness of fit:	Compressive strength		splitting tensile strength	
	Grade 30	Grade 40	Grade 30	Grade 40
SSE	11.14	76.32	0.224	0.8556
R-square	0.9886	0.945	0.955	0.8451
Adjusted R-square	0.9812	0.926	0.9261	0.7914
RMSE	0.8922	1.713	0.1265	0.1814

Furthermore, the correlation between concrete grade 30 and 40 experimental and the predicted strength for the compressive strength and splitting tensile strength is plotted in Fig. 9 and 10 respectively. It was confirmed that the model agrees with the experimental results and is good for self-compacting concrete strength prediction. Although it is observed that model is more reliable in predicting compressive strength than splitting tensile strength. This is in line with the research of [21]

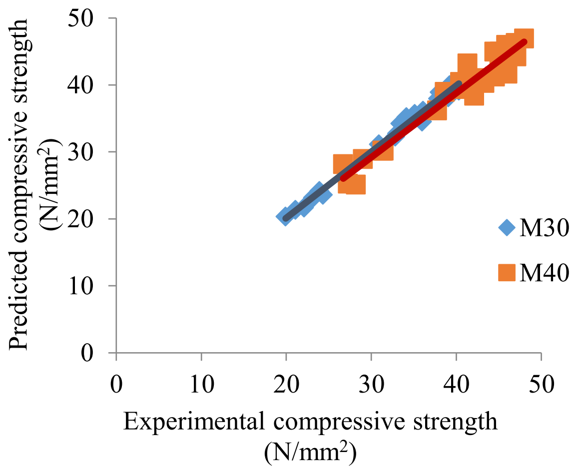

Fig. 9. Relationship between M30 and M40 Experimental and Model predicted Compression strength of SCC.

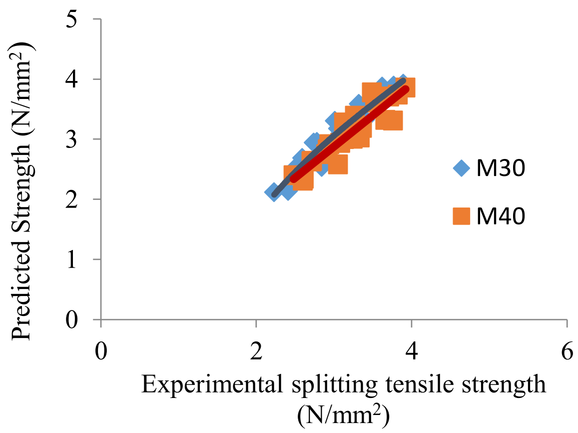

Fig.10. Relationship between M30 AND M40 Experimental and Model predicted Splitting Tensile strength of SCC

5.0 CONCLUSIONS

1) Incorporating 10% replacement of cement with RHA as a pozzolana viable in production of SCC.
2) The compressive strength and splitting tensile strength of concrete increase at an increase in SP dosage from 0.6% up to1.3% and 1.65% for concrete M30 and M40 respectively and decrease with further increase up to 2.0% for both grade of concrete.
3) The optimum dosage of super-plasticizer which satisfies both the fresh and hardened properties of SCC was found to 1.3% for both M30 and M40 grade of concrete.
4) The experimental strength and the model predicted strength shows a good prediction accuracy with R^2 of 0.9886, 0.945 and 0.955, 0.8556 for M30 and M40 for compressive and splitting tensile strengths respectively
5) The proposed models are robust for determination of compressive strength and splitting tensile of self-compacting concrete.

5.2 RECOMMENDATIONS

1) The result of compressive strength and splitting tensile strength of SCC shows that with excess addition of SP into the concrete, the strength decreases. Therefore, the use of SP above 1.65% is not advisable.
2) Regression model can be used to predict the Compressive strength and splitting tensile strength of SCC.

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