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OPTIMIZING THE EFFECT OF WATER CEMENT RATIO ON MECHANICAL PROPERTIES OF CONCRETE PRODUCED WITH STEEL SLAG

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Abstract–Steel is produced from iron ore and purification of metal scrap, leading to manufacture of hundreds of tonnes of steel slag each year. Based on developing interest on the utilization of waste materials as alternative to natural aggregates, this study investigated the effect of water-cement ratios (w-c) on the optimum replacements of granite with steel slag in concrete. Slags from Prism Nigeria Limited (PNL), Ikirun and Ife Iron and Steel Nigeria Limited (ISN), Ile-Ife were used to replace granite by 0, 40, 50 and 60% in concrete. A mix ratio of 1:2:4 was adopted and batching was done by weight with w-c of 0.4, 0.5, 0.6 and 0.7 using cement content of 300 kg/m^3. Fifty-six concrete cubes (150 by 150 by 150 mm), 56 cylindrical concrete samples (150 by 300 mm) and 56 concrete beam samples (100 by 100 by 500 mm) were produced and cured in water for 28 days. Compressive Strength (CS), Split Tensile Strength (STS) and Flexural Strength (FS) were carried out on hardened concrete using universal testing machine. The results of the CS, STS and FS were subjected to Analysis of Variance (ANOVA) at $p < 0.05$. The study concluded that strengths of concrete decreased with increase in w-c and addition of steel slag improved concrete properties. The results of the ANOVA of CS, STS and FS were all significant ($p = 0.0001$). Towards reduction in environmental pollution, 60% PNL and 40% ISN with w-c of 0.4 are therefore recommended for application in reinforced concrete.

Keywords: Water Cement Ratio, Steel Slag, Concrete, Strengths, Optimization

1. Introduction

Concrete is widely used as construction material in the universe (Adebara *et al.,* 2016; Anifowose *et al.,* 2018; Odeyemi *et al.,* 2021; Ige *et al.,* 2017; Ige *et al.,* 2018; Salaudeen and Anifowose, 2022; Abdulwahab *et al.,* 2024). The aggregates formed 75% of the concrete volume and play a substantial role in different concrete properties. Conventional concrete consists of sand as fine aggregate and gravel, limestone or granite in various sizes and shapes as coarse aggregate. The need for waste materials as an alternative for aggregate replacement is increasing and numerous studies have been conducted on the use of different waste materials as aggregate replacement (Ravikumar *et al.,* 2015; Odeyemi *et al.,* 2015; Anifowose *et al.*, 2017; Adeyemi *et al.,* 2019; Anifowose *et al.*, 2019; Odeyemi *et al.,* 2023).

Steel slag (SS) is a by-product of steel manufacturing which is categorized in line with the steelmaking technique (Anifowose *et al.,* 2019). The molten liquid of steel slag is a complicated solution of silicates and oxides that solidifies on cooling and forms steel slag. However, steel slag is a non-metallic product blended with fused oxides which might be evolved concurrently with steel in either electric or basic oxygen furnaces (Sharma *et al.,* 2015). Utilization of environmental friendly materials is of major importance and steel slag could be substitute for coarse aggregates in concrete (Padmapriya *et al.,* 2015; Anifowose *et al.,* 2017; Anifowose *et al.,* 2024). Most often, steel slag are disposed around the steel producing centres posing environmental threats. Today, emphasis is on the avoidance of waste generation, recycling and reuse of waste, and minimising the adverse impact of disposal on the environment (Olonade *et al.,* 2015; Adedokun *et al.,* 2021). In South Western part of Nigeria, there are numbers of integrated steel plants producing steel with large deposit of steel slag. Therefore, there is need for the utilization of steel slag in concrete production in Nigeria as the cost of natural aggregates (fine and coarse aggregate) is becoming higher and more so, to avert environmental threat posed by steel slag disposal around steel company.

In engineering practice, the strength of concrete cured at a particular age in water is assumed to depend primarily on two factors: The Water/Cement Ratio (W-C) and the degree of compaction. When concrete is absolutely compacted, it's given strength is inversely proportional to W-C (Neville, 2011). Concrete strengths depends majorly on w-c if the mix is workable (Shetty, 2000). The W-C is the main factor in the strength of fully compacted concrete in practice (Neville, 2011). W-C is a significant factor for manufacturing of concrete. Strict control on the use of W-C on site could be a better deal required to get best concrete (Varma 2015). However, utilization of much water for production of concrete mix has been a common practice to foreman and some supervisor/engineer in Nigeria construction industry. This calls for assessment of varying w-c for production of steel-slag-concrete and its effect on mechanical properties.

2. Materials and Methods

2.1 Materials

Water, fine aggregate, coarse aggregate (granite), Slags from Prism Nigeria Limited (PNL), Ikirun, and Ife Iron and Steel Nigeria Limited (ISN) were used for concrete production. The granite, PNL and ISN has specific gravity (SG), aggregate impact value (AIV) and aggregate crushing value (ACV) of 2.69, 12.5% and 24.6% ; 2.71, 7.14% and 19.67% ; and 2.75, 7.5% and 22.5%, respectively. Oxide composition of the PNL and ISN were determined using x-ray fluorescence (XRF) techniques.

2.2 Methods

This study investigated the influence of water content on optimum replacement of granite with steel slag in concrete production. The substitutions of crushed stone (granite) with steel slag were 0, 40, 50 and 60%. Mix ratio 1:2:4 was used and batched by weight with W-C of 0.4, 0.5, 0.6 and 0.7 (in accordance with Table A.7 of BS 8500-1:2006) and cement content of 300 kg/m^3. Total number of 56 concrete cubes of sizes 150 by 150 by 150 mm (24 cubes for Prism Steel Slag, 24 cubes for Ife Steel Slag and 8 cubes for conventional concrete), 56 concrete cylinder samples of sizes 150 by 300 mm (24 for Prism Steel Slag, 24 for Ife Steel Slag and 8 for conventional concrete) and 56 concrete beam samples of sizes 100 by 100 by 500 mm (24 for Prism Steel Slag, 24 for Ife Steel Slag and 8 for conventional concrete) were produced. The concrete specimens were cured for 28 days (been age that concrete is expected to gain characteristics strength). At the end of each curing ages, densities were determined on the cubes while CS, STS and FS test were determined on the concrete cubes, cylindrical concrete samples and beam concrete samples respectively. Calculations of Ratio 1:2:4 mix proportions based on cement content of 300 kg/m^3 are given in Table 1. The hardened concrete was subjected to Analysis of variance (ANOVA) at $p < 0.05$ in order to observe the significance level of CS, STS and FS. Response Surface Method (RSM) was adopted for the analysis and the design was base historical data design using Design-Expert 7.0 version.

Table 1: Calculation of Ratio 1:2:4 Mix Proportions used

Concrete Property	Ratio 1:2:4 Mix based on Cement Content of 300 kg/m^3
CS	**Concrete Cubes (** $V = L \times B \times H$ **)** Volume of Cube $\Rightarrow 0.15 \times 0.15 \times 0.15m = 0.003375m^3$ One concrete cube $\Rightarrow 0.003375m^3 \times 300kg/m^3 = 1.0125kg$ 20% shrinkage and waste $\Rightarrow 0.2 \times 1.0125 = 0.2025kg$ Cement for one concrete cube $\Rightarrow 1.0125 + 0.2025 = 1.215kg$ Weight of cement for two concrete cubes (28 days) $\Rightarrow 1.215 \times 2 = 2.43kg$

STS	**Cylinder Specimen (** $V = \pi r^2 h$ **)** Volume of Cylinder $\Rightarrow \pi(0.075^2) \times 0.3 = 0.005304 m^3$ One concrete cylinder $\Rightarrow 0.005304 m^3 \times 300 kg/m^3 = 1.5912 kg$ 20% shrinkage and waste $\Rightarrow 0.2 \times 1.5912 = 0.31824 kg$ Cement for one cylinder $\Rightarrow 1.5912 + 0.31824 = 1.9094 kg$ Weight of cement for two concrete cylinder (28 days) $\Rightarrow 1.9094 \times 2 = 3.8188 kg$
FS	**Concrete Beam (** $V = L \times B \times H$ **)** Volume of Beam $\Rightarrow 0.5 \times 0.1 \times 0.1 m = 0.005 m^3$ One concrete Beam $\Rightarrow 0.005 m^3 \times 300 kg/m^3 = 1.5 kg$ 20% shrinkage and waste $\Rightarrow 0.2 \times 1.5 = 0.3 kg$ Cement for one concrete Beam $\Rightarrow 1.5 + 0.3 = 1.8 kg$ Weight of cement for two concrete Beam (28 days) $\Rightarrow 1.8 \times 2 = 3.6 kg$

3. Results and Discussion

3.1 XRF of PNL and ISN

The major compounds of steel slag as presented in Table 2 are SiO_2, Fe_2O_3, Al_2O_3, and CaO. The major compositions are in agreement with previous study by Kothai and Malathy (2014), and Subramani and Ravi (2015), Abrol *et al.*, (2016), and Adedokun *et al.*, (2018). Ferric oxide (Table 2) has the highest content, this normally result in strong bond formation within concrete materials (Adedokun, *et al.*, 2024).

Table 2: Oxide Composition of Steel Slag

Oxides	PNL Composition (%)	ISN Composition (%)
SiO_2	35.68	36.06
Al_2O_3	11.28	10.02
Fe_2O_3	46.93	47.78
CaO	11.07	6.34
MgO	-	0.00
K_2O	0.87	1.35
MnO	6.89	6.77
TiO_2	0.94	1.97
P_2O_5	0.33	0.28

3.2 Compressive strength

The PNL-CS results (Figure 1) indicated that the CS reduced as the W-C increased. W-C of 0.4 has the highest CS while W-C of 0.7 has the least CS. The CS increased up to 40% PNL and reduced at 50% PNL substitutes of crushed stone but further increased at 60% PNL replacements in W-C of 0.4, 0.5, 0.6 and 0.7. The improvement in strength is due to the shape, size, surface texture and strength (AIV and ACV) of the PNL, as well as low W-C which provides better bonding between particles and cement paste. The properties of aggregate, especially its shape and surface texture, affect the ultimate strength in compression than the strength in tension or the cracking load in compression (Neville, 2011). However, concrete with low W-C improve strength characteristics of concrete while higher W-C will give consistent decrease in strength (Zongjin, 2011; Neville, 2011; Rahmani *et al.*, 2012; Varma, 2015; Anifowose *et al.*, 2021). The maximum CS of PNL-Hardened-Concrete-Cube obtained at 60% PNL correspond to 60% of steel slag (by weight of granite) reported by Gokul *et al.,* (2012), Subramani and Ravi (2015), Thangaselvi (2015) and Ravikumar *et al.,* (2015).

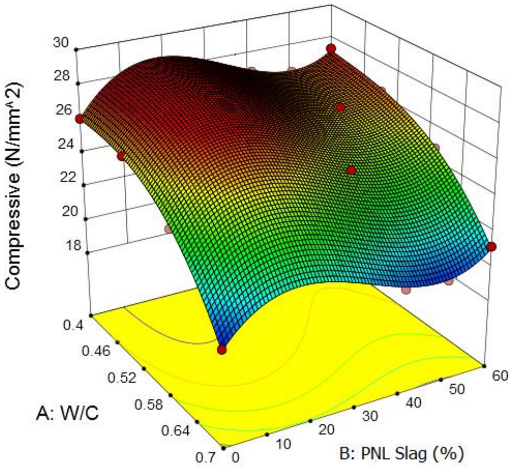

Figure 1: Effect of W/C and PNL on CS

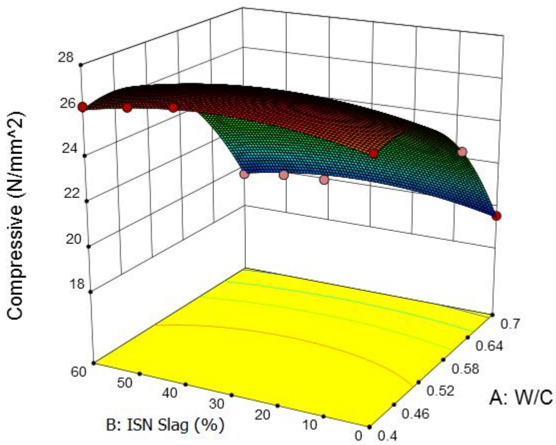

Figure 2: Effect of W/C and ISN on CS

The ISN-CS results (Figure 2) also indicated reduction in CS as the W-C increased. W-C of 0.4 has the highest CS while W-C of 0.7 has the least CS. The CS increased up to 40% ISN and further reduced at 50% ISN and 60% ISN substitutes of crushed stone for W-C of 0.4, 0.5, 0.6 and 0.7. The improvement in strength is also due to the shape, size, surface texture (due to pores) and strength (AIV and ACV) of the ISN, as well as low W-C which provides better bonding between particles and cement paste. Aggregate with smooth surface particle will have less bonding area with concrete matrix than a rough particle of the same volume. Hence, rough textured aggregate develops higher bond strength, thereby improving concrete strength (Shetty, 2000). The optimum replacement with highest CS of concrete cubes at twenty-eight days curing age using ISN was found to be 40% for all W-C. The maximum CS of ISN-Hardened-Concrete-Cube obtained at 40% ISN is in agreement with the previous study reported by Qurishee *et al.*, (2016) and Anifowose *et al.,* (2017). The PNL-Hardened-Concrete-Cube possess better CS than the ISN-Hardened-Concrete-Cube as a result of the physical properties (SG, AIV and ACV) earlier reported. However, the PNL-Hardened-Concrete-Cube and ISN-Hardened-Concrete-Cube has better CS than the conventional concrete cube (control mix). This is due to the smooth (polish) surface of the granite which gives less bonding characteristics in the concrete matrix (Shetty, 2000; Newman and Choo, 2003; Zongjin, 2011; Neville, 2011).

3.3 Splitting tensile strength

Figures 3 and 4 describe the STS result of PNL-Hardened-Cylindrical-Concrete and ISN-Hardened-Cylindrical-Concrete. The PNL-Split-Tensile strength (Figure 3) reduced as the W-C increased. The PNL-STS increased up to 40% PNL and reduced at 50% PNL substitutes of crushed stone but further increased at 60% PNL replacements at W-C of 0.4, 0.5 and 0.6. However, for W-C of 0.7, the STS increased as the granite substitute with PNL increased. The ISN-STS results (Figure 4) also indicated reduction in strengths as the W-C increased. The STS increased up to 40% ISN and reduced at 50% INS and 60% ISN substitutes of granite for W-C of 0.4, 0.5, 0.6 and 0.7. The improvement in STS is due to the shape, size, surface texture and strength (AIV and ACV) of the PNL and ISN, as well as low W-C which provides better bonding between particles and cement paste (Neville, 2011).

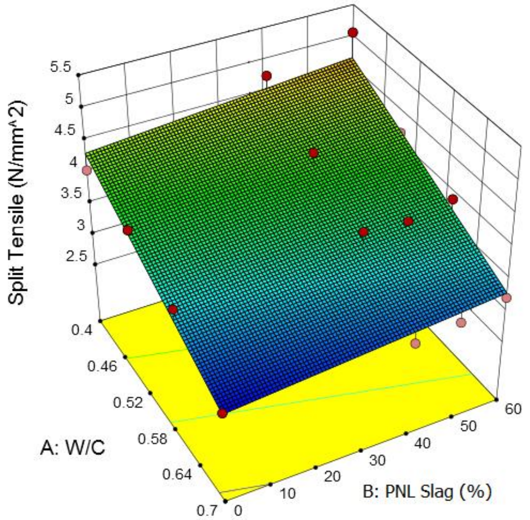

Figure 3: Effect of W/C and PNL on STS

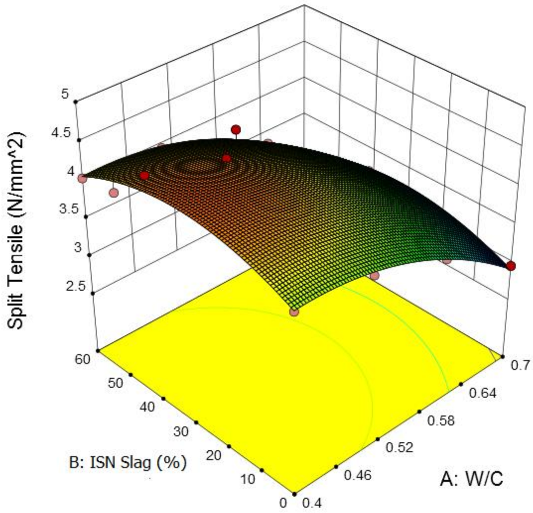

Figure 4: Effect of W/C and ISN on STS

The PNL-Hardened-Cylindrical-Concrete possess better STS than the ISN-Hardened-Cylindrical-Concrete. Hence, both PNL and ISN possess better STS than the control mix due to physical properties of the steel slag. The maximum STS of PNL-Cylinder obtained at 60% PNL is in agreement with the previous study reported by Subramani and Ravi (2015), Ravikumar *et al.*, (2015) and Thangaselvi (2015), while 40% ISN correspond to the study of Kothai and Malathy (2013), Qurishee *et al.*, (2016), and Adedokun *et al.*, (2019).

3.4 Flexural strength

The results of the PNL-Hardened-Concrete-Beam and ISN-Hardened-Concrete-Beam are shown in Figures 5 and 6. The FS increased up to 40% PNL and reduced at 50% PNL and 60% PNL (Figure 5) substitutes of granite for W-C of 0.4, 0.5, 0.6 and 0.7. The ISN-FS (Figure 6) also indicated reduction in FS as the W-C increased. The FS increased up to 40% ISN and reduced at 50% INS and 60% ISN substitutes of granite for W-C of 0.5, 0.6 and 0.7. However, for W-C of 0.4, the FS reduced as the granite substitute with ISN increased at 40% ISN and witnessed increment in FS at 50% ISN but the FS further reduced at 60% ISN. The improvement of both PNL-FS and ISN-FS is due to the surface texture, and physical properties (SG, AIV and AC) of PNL and ISN. The surface texture of an aggregate is an issue where FS is important, or for very high-strength concretes. In both cases, rougher textures give greater strengths, because the aggregate-cement paste bond is improved (Newman and Choo, 2003).

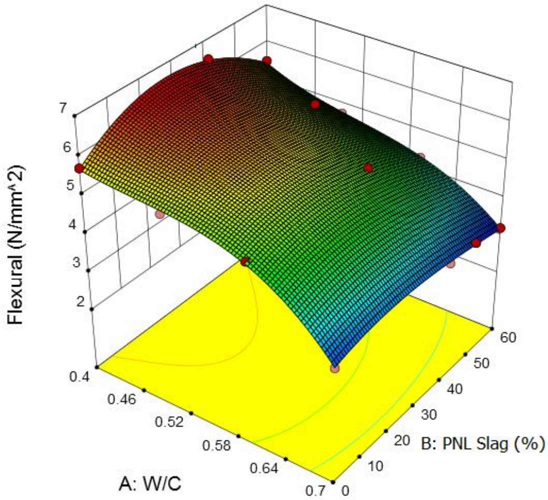

Figure 5: Effect of W/C and PNL on FS

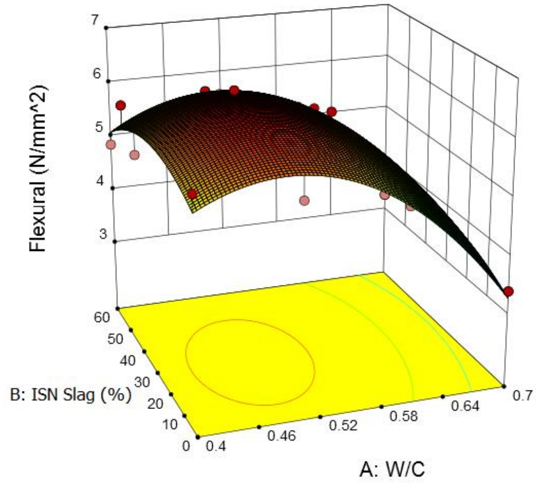

Figure 6: Effect of W/C and ISN on FS

The optimum replacement of granite for production of PNL-FS was found to be 40% PNL for all W-C. However, optimum replacement at 28 days with highest FS for W-C of 0.4 was 50% ISN while 40% ISN was found to be the optimum replacement for W-C of 0.5, 0.6 and 0.7. The maximum FS with 40% PNL and ISN is in agreement with the previous finding by Kothai and Malathy (2013) while 50% ISN with maximum FS at W-C of 0.4 correspond to the study of Sharma *et al.*, (2015), and Adedokun *et al.*, (2019). The PNL-FS and ISN-FS possess better FS than the conventional concrete.

3.5 Effect of process optimization on hardened concrete

In determining the maximum response value of PNL and ISN hardened concrete, two factors were chosen as follows: A, W-C (0.4-0.7) and B, PNL/ISN Slag (0-60%) at two levels. Response Surface Method (RSM) was adopted for the analysis of the optimum condition that maximized CS, STS and FS. The optimal plots for the response variables are given in Figures 7 and 8. The ramp profiles (optimal plots) illustrate the desirability of hardened concrete as a function of the factors. A desirability of 0.906 and 0.956 for PNL and ISN hardened concrete with a maximum response value of CS (27.35 and 26.9627 N/mm^2); STS (4.53174 and 4.39218 N/mm^2); and FS (6.55026 and 6.16498 N/mm^2) is obtained at A = 0.4 and 0.47; and B = 36.07 and 28.85%, respectively.

Analysis of Variance (ANOVA) method was employed at $p < 0.05$ in order to estimate the significance and accuracy level of the model which resulted in Equations (1), (2), (3) (4), (5) and (6) for PNL-CS (Cubic Model), PNL-STS (Linear Model), PNL-FS (Cubic Model), ISN-CS (Quadratic Model), ISN-STS (Quadratic Model), and ISN-FS (Quadratic Model), respectively. The ANOVA of the models are presented in Tables 3 and 4.

$$PNL - CS = +26.59 - 2.79\mathrm{A} - 3.17\mathrm{B} + 0.096AB - 2.06A^2 - 1.08B^2 + 0.27A^2B + 0.27AB^2 - 0.67A^3 + 3.58B^3 \quad (1)$$

$$PNL - STS = +3.81 - 0.69\mathrm{A} + 0.18\mathrm{B} \quad (2)$$

$$PNL - FS = +5.68 - 1.01\mathrm{A} - 0.47\mathrm{B} + 5.433\times10^{-3}AB - 0.55A^2 - 0.69B^2 + 0.25A^2B + 0.37AB^2 - 0.50A^3 + 0.11B^3 \quad (3)$$

$$ISN - CS = +25.93 - 3.21\mathrm{A} + 0.075\mathrm{B} + 0.014AB - 2.42A^2 - 0.70B^2 \quad (4)$$

$$ISN - STS = +4.18 - 0.57\mathrm{A} + 0.014\mathrm{B} + 8.241\times10^{-3}AB - 0.33A^2 - 0.35B^2 \quad (5)$$

$$ISN - FS = +6.01 - 0.96\mathrm{A} - 0.049\mathrm{B} + 0.11AB - 1.25A^2 - 0.47B^2 \quad (6)$$

The Predicted R^2 of 0.9651; 0.7557; 0.9449; 0.9849; 0.9309 and 0.7806, for PNL-CS; PNL-STS; PNL-FS; ISN-CS; ISN-STS; and ISN-FS, respectively are in reasonable agreement with the Adjusted R^2 of 0.9946; 0.8204; 0.9865; 0.9891; 0.9593 and 0.9193. The "Adequate Precision" ratio of 49.968 (PNL-CS), 15.838 (PNL-STS), 34.596 (PNL-FS), 41.105 (ISN-CS), 24.342 (ISN-STS) and 16.966 (ISN-FS) are higher than 4, which are desirable for the models' and indicates an adequate signal (Ogunleye *et al.*, 2018; Busari *et al.*, 2019, Adedokun *et al.*, 2021; Adedokun and Anifowose, 2022).

The models' *F* values of 310.27, 35.26, 122.65, 274.38, 71.70 and 35.18 for PNL-CS, PNL-STS, PNL-FS, ISN-CS, ISN-STS, and ISN-FS, respectively, were all significant as presented in Tables 3 and 4.

Figure 7: Optimal Plot of PNL-Hardened Concrete

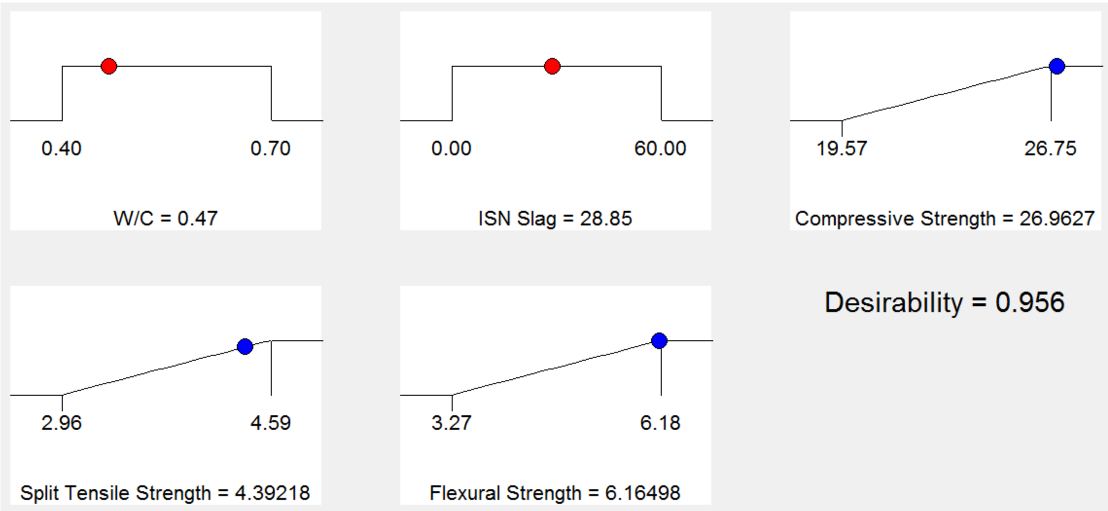

Figure 8: Optimal Plot of ISN-Hardened Concrete

Table 3: ANOVA for PNL-Hardened-Concrete

Responses	Source	Sum of square	*df*	Mean square	*F* ratio	*p value*

CS	Model	106.96	9	11.88	310.27	0.0001*
	Residual	0.23	6	0.038		
	Cor total	107.19	15			
R^2 = 0.9979; Adj R^2 = 0.9946; Pred R^2 = 0.9651; Adeq precision = 49.968						
STS	Model	4.50	2	2.25	35.26	0.0001*
	Residual	0.83	13	0.064		
	Cor total	5.33	15			
R^2 = 0.8444; Adj R^2 = 0.8204; Pred R^2 = 0.7557; Adeq precision = 15.838						
FS	Model	15.60	9	1.73	122.65	0.0001*
	Residual	0.085	6	0.014		
	Cor total	15.68	15			
R^2 = 0.9946; Adj R^2 = 0.9865; Pred R^2 = 0.9449; Adeq precision = 34.596						

***Significant at p < 0.05**

Table 4: ANOVA for ISN-Hardened-Concrete

Responses	Source	Sum of square	*df*	Mean square	*F* ratio	*p value*
CS	Model	111.45	5	22.29	274.38	0.0001*
	Residual	0.81	10	0.081		
	Cor total	112.26	15			
R^2 = 0.9928; Adj R^2 = 0.9891; Pred R^2 = 0.9849; Adeq precision = 41.105						
STS	Model	3.47	5	0.69	71.70	0.0001*
	Residual	0.097	10	9.682×10^{-3}		
	Cor total	3.57	15			
R^2 = 0.9729; Adj R^2 = 0.9593; Pred R^2 = 0.9309; Adeq precision = 24.342						
FS	Model	13.20	5	2.64	35.18	0.0001*
	Residual	0.75	10	0.075		
	Cor total	13.95	15			
R^2 = 0.9462; Adj R^2 = 0.9193; Pred R^2 = 0.7806; Adeq precision = 16.966						

***Significant at p < 0.05**

4. Conclusion

Influence of water content on mechanical properties of slag concrete has been examined and the following conclusions were drawn:

i. The SG of aggregates shows that PNL and ISN values were higher than granite; AIV results indicated that PNL and ISN gave better relative degree of resistance to an unexpected shock or impact than granite; and ACV shows that PNL and ISN can withstand a gradually applied compression load than granite.

ii. The behaviour of the PNL-Hardened-Concrete and ISN-Hardened-Concrete indicated consistent decreased in CS, STS and FS as the W-C increases. Except for ISN-FS where the FS increased from 0.4W-C to 0.5W-C and further decreased. W-C of 0.4 has the highest CS, STS and FS while W-C of 0.7 has the least CS, STS and FS. However, addition of PNL and ISN improve the CS, STS and FS of hardened concrete. And the *F* values of the models' (CS, STS and FS) were less than 0.05, which proved that the models' were significant.

iii. The PNL that produced maximum CS and FS was 60 and 40% respectively for all W-C. Hence, PNL that produced maximum STS for W-C of 0.4, 0.6 and 0.7 was found to be 60% PNL while 0.5 W-C had optimum replacement of 40% PNL. ISN that produced maximum CS and STS was found to be 40% for W-C of 0.4, 0.5, 0.6 and 0.7; the optimum replacement of FS for W-C of 0.4 was 50% ISN while 40% ISN was found to be the optimum replacement for W-C of 0.5, 0.6 and 0.7. Conclusively, the optimum replacement predicted by the model was 36.07% at W-C of 0.4 and 28.85% at 0.47 W-C for PNL and ISN, respectively.

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