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Optimization of Calcined Beans Pod Ash – Cement Blended Concrete Mix Using Taguchi Method

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Abstract. This study investigated the optimization of calcined beans pod ash (BPA) - cement concrete mix using the Taguchi method. Concrete is a widely used building material with various performance requirements. These requirements are mostly influenced by concrete constituent materials and mixtures proportion obtained from concrete mix design. But improper mix design can result in inherent defects or local imperfections, which can significantly deteriorate the performance properties of concrete and jeopardize the structural integrity and durability of concrete structure. Taguchi method of optimization was employed to address these challenges. It involves identifying key factors (water – cement ratio, percentage of BPA – cement replacement, fine to total aggregate ratio and super-plasticizer dosage), selecting suitable levels for these factors, and conducting experiments to determine the optimum combination of factors. The effects of these variables on concrete slump flow (SF), compressive strength (F_{cu}), and split tensile strength (F_y) were evaluated. The results of SF, F_{cu} and F_y of BPA – cement concrete show significant improvement of 23.74%, 21.72% and 21.43% respectively, when cement was partially replaced with BPA from 5% to 20%. Likewise, an improvement of 5.97%, 5.69% and 5.37% for SF, F_{cu} and F_y of BPA – cement concrete, when the dosage of super-plasticizer in concrete mix was varied from 6% to 12%. A respective optimal parameter combination for BPA – cement concrete slump and strengths were obtained at 0.40, 5%, 0.4, 6 ml/kg of cement and 0.35, 5%, 0.4, 6 ml/kg of cement for W-C, BPA, F-T Agg, SP respectively.

Key words: Beans-pod, Super-plasticizer, Concrete, Taguchi, Slump, Strength.

1. Introduction

Concrete is a composite stone-like building material made by man. Concrete is produced from the combination of cement with both fine and coarse aggregate, water and sometimes additives, like pozzolans, plasticizers, etc. Water allows concrete constituent materials bind and set together. Concrete comes in different mix ratio depending on the required performance characteristics. Concrete can be engineered to meet a variety of performance requirements, and sometimes with reinforcements to provide for the shortfall in tensile strength when compared with compressive strength. Owing to its strength properties, concrete materials are now being used in the construction of dams, highways, buildings, etc. (Jezek, 2009). The most common type of cementitious material used in concrete production is Portland cement. Other cementitious materials include lime, pozzolan and any combination of these materials. The quantity and quality of cementitious materials determine the rate at which concrete develops strength (Joseph et al., 2014).

Also, concrete properties depend largely on the properties of its aggregate constituents because it constitutes typically 75% or more of the concrete volume (Bissonnette et al., 1999). Aggregates are in various shapes, sizes and materials, ranging from fine aggregate to coarse aggregate. The desired performance characteristics of concrete informs the choice of aggregate and its corresponding particle size distribution. For instance, high aggregate density will result in higher concrete density (Ouda, 2015).

Another essential component in making concrete is water, which when combined with cement creates a paste that holds the aggregate together. Through a process known as hydration, water causes concrete to harden and water used for the process of cement hydration must be potable. Water plays a crucial role in the production of concrete, as the ratio of water to cement is one of the most significant factors in determining its quality and characteristics. (Chen et al., 2012). A careful balance in water to cement ratio in concrete production makes the concrete workable and strong (Shi *et al,* 2012). Meanwhile, Wonsiri (2006) stated that poor mix design can result in local imperfections or inherent flaws. The mechanical properties of the material may be severely compromised by these flaws, endangering the structural stability and durability of the entire structure, as seen in volume of leakage of water that occurs globally. Over 32 billion m^3 of treated water is lost annually due to leaks in tanks and distribution systems. (Afifi et al., 2018). Therefore, efforts to ensure resource utilization that is ecologically sound, efficient and socially effective stand out as a key issue for the 21st century (FAOUN, 2000). This is achieved by improving the performance of concrete structures in a way to contribute to society's sustainable growth, and it has emerged as a key issue from the perspective of the environment (Kanematsu et al., 2009).

This is a type of concrete that can meet certain performance and uniformity requirements that are sometimes difficult to meet when using conventional concrete components, standard mixing techniques and curing procedures. Self-compacting concrete (SCC) is a specially designed material made of cement, aggregates, water, and admixtures with a number of new components, such as colloidal silica, pozzolanic materials, and chemical admixtures, to address certain requirements, such as high flow-ability, compressive strength, high workability, enhanced resistances to chemical or mechanical stresses, lower permeability, durability, and resistance against segregation under dense reinforcement conditions. (Johnson 2022). It is also crucial to remember that water/cement ratio, aggregates, admixtures, compaction, curing, cement properties and homogeneity of concrete, amongst others are the various parameters or factors that influence concrete performance. Garcia (2018) also confirm that water/cement ratio has the largest influence on concrete performance.

Ghassan et al. (2016) defined pozzolan as a siliceous material used to partially replace cement in concrete production. Pozzolans react with calcium hydroxide and other alkalis in a cementitious reaction in order to minimise the resultant heat of hydration generated from concrete production, thereby improving concrete workability and strength. Tijani et al. (2018) and Altwair et al. (2011) affirmed that pozzolanic activity in pozzolans are better enhanced at optimum burning temperature and time. Pozzolans can be cheaply sourced from volcanic mineral deposits, fly ash, fired and crushed clay and ash of some agricultural wastes, amongst others. Hence, this study aimed at optimising concrete mix involving beans pod ash (BPA) – cement blended concrete for improved performance.

The adoption of Taguchi method of optimization involves identifying the primary function and its side effects, uncontrolled factors, testing condition, quality characteristics, objective function to be optimized, control factors and their levels; selection of an appropriate orthogonal array and construction of matrix that will be used to conduct experiment. Thereafter, responses obtained from experimental activities would be examined and the optimum influencing factor level and its performance would be predicted from developed model equations and verification experiment conducted. Factors and their corresponding levels are mostly decided based on the knowledge driven concrete practice from reviews of methodology in existing work and the need to reflect on the wide range of limits for the development of an informed mix optimization (Smith, 2023). In this study, four (4) levels are considered for four (4) independent variables.

2. Materials and Method

Fakayode et al. (2014) and Ajeigbe et al. (2010) affirmed that Nigeria contributes at least 45% of cowpea production per annum worldwide; amounting to over 3.4 million tons of dried cowpea. The various species of cowpea include Glycine Max (Soya Beans), Vigna Vexillata (Otili), Stenocarpastylosa (Feregede), Phaseolus Vulgaris (kokondo) and Vigna Unguiculata (Big White, Small White, Oloyin and Drum), amongst others (Olabanji et al., 2018). The pod of a variety of cowpea known as Vigna Unguiculata (drum beans) was used for this experiment. Beans pod was burnt to ashes using gas burner. Optimum calcination parameters as obtained by Joseph et al. (2023) were used. The beans pod ash (BPA) was calcined in a muffle furnace at 738^{o}C for 3.45-hours. Table 1 provides information about the pozzolanic oxides of calcined BPA used. Limestone Portland cement which conforms to ASTM C595/C595M-12 was used. River sand free from deleterious material was obtained from Awere river and crushed granite from quarry, all in Ede, Osun State Nigeria, were used for this experiment. Commercially available rapid setting superplasticizer (MasterGlenium SKY504) obtained from MasterBuilders, Lagos Nigeria, was used as chemical additive for this experiment. Physical properties for cement, beans pod ash, super-plasticizer, river sand and crushed granite are presented in Table 2.

Table 1. Oxides Composition of Beans Pod Ash (Joseph et al., 2023)

Oxides	BPA (%)
SiO_2	34.2
Al_2O_3	10.33
Fe_2O_3	9.31
CaO	13.8
MgO	6.11
Mn_2O_5	2.84
K_2O	5.4
Pb_2O_5	7.92
SO_3	1.81
Na_2O	1.13
TiO_2	0.05
Cl	0.03
Cr_2O_3	0.06
SrO	0.16
LOI	5.08
$SiO_2 + Al_2O_3 + Fe_2O_3$	53.84

Table 2. Concrete Constituent Material Properties

Material Used	Specific Gravity	Appearance
Portland Limestone Cement	2.25	Dark Gray Powder
Beans Pod Ash	1.35	Blackish Powder
Super-plasticizer	1.115	Whitish to Straw Coloured Liquid
River Sand	2.65	Brownish Grains
Crushed Granite	2.67	Whitish Gray Crushed Stones

2.1. Experimental Design

Experimental design (orthogonal array) involved the adoption of Taguchi method, using the earlier identified variables (independent and dependent variables) that influences the behaviour of SCC and defining the procedure of data analysis. Table 3 shows the factors considered and their various levels. These factors include water – cement (W-C) ratio with values ranging from 0.3 to 0.45, partial replacement of cement with BPA ranging from 5% to 20%, introduction of chemical admixture ranging from 600ml/100kg of cement to 1200ml/100kg of cement and fine to total aggregate (F-T Agg) ratio ranging from 0.25 to 0.40. The equal spacing for each of the factor levels was to respect the corresponding preconditioning for the Taguchi approach of design of experiment.

Table 3. Experimental Parameters and Levels

Parameters	**Unit**	**Level of Parameter**			
		1	2	3	4
W-C Ratio	Ratio	0.3	0.35	0.4	0.45
BPA	%	5	10	15	20
F-T Agg Ratio	Ratio	0.25	0.3	0.35	0.4
SP	%	6	8	10	12

Concrete samples were produced for sixteen (16) different mixes as obtained from experimental design in Table 4, in order to establish the contribution of the independent factors on the resulting mixture. These independent variables are placed on four (4) levels, so as to ensure enough experimental data are generated for obtaining model for performance characteristics of concrete, which shall be used to optimize concrete mixture proportion in order to improve on specific properties of SCC. The concrete samples shall be tested in fresh state for workability using slump cone, and hardened (cured) state for strength performance.

Table 4. Standard L16 Orthogonal Array

Independent Variables					**Dependent Variables**		
Mix ID	W-C Ratio	BPA (%)	F-T Agg Ratio	SP Content	Slump Flow (mm)	Fcu (N/mm^2)	Fy (N/mm^2)
M 1	0.3	5	0.25	6	-	-	-
M 2	0.3	10	0.3	8	-	-	-
M 3	0.3	15	0.35	10	-	-	-
M 4	0.3	20	0.4	12	-	-	-
M 5	0.35	5	0.3	10	-	-	-
M 6	0.35	10	0.25	12	-	-	-
M 7	0.35	15	0.4	6	-	-	-
M 8	0.35	20	0.35	8	-	-	-
M 9	0.4	5	0.35	12	-	-	-
M 10	0.4	10	0.4	10	-	-	-
M 11	0.4	15	0.25	8	-	-	-
M 12	0.4	20	0.3	6	-	-	-
M 13	0.45	5	0.4	8	-	-	-
M 14	0.45	10	0.35	6	-	-	-
M 15	0.45	15	0.3	12	-	-	-
M 16	0.45	20	0.25	10	-	-	-

2.2. Concrete Sample Preparation

Manual method of fresh concrete production that conforms to BS 1881-125 (2013) was adopted. Batching by weight, being the most reliable batching method, when compared with batching by volume for laboratory activities, was applied in mixing the concrete constituents. Volume of mixing water obtained from water – cement ratio as specified in the experimental design was carefully dosed on the dry mixture to obtain homogeneous mix. Sixteen (16) different mixes of fresh concrete were produced following same procedure in BS 1881-125 (2013) and in line with batching specification in Table 5 while Figure 1 shows the flow chart of tests carried out on BPA – Cement concrete.

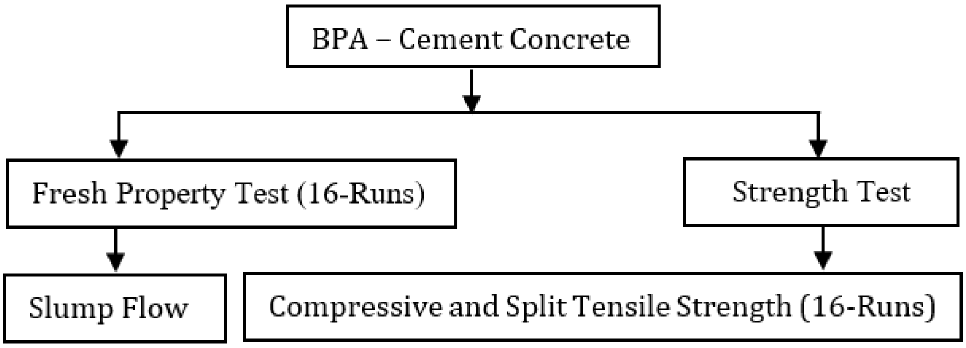

Fig 1. Flow Chart of Test on BPA – Cement Concrete.

2.3. Taguchi Method

Taguchi apply statistical methods, such as analysis of variance (ANOVA), to analyse the experimental data, determine the significance and contribution of each parameter on the response variables and identify the optimal parameter settings that result in the desired performance. In order to optimize the concrete mix for better performance, Taguchi adjust the parameter settings based on the analysis results to achieve the desired performance. This was achieved through finding combination of parameter levels that maximize concrete performance in slump flow, compressive and split tensile strength. Minitab 17 software was used for result analysis and data base development and mathematical model developed for concrete performance, at fresh and hardened states, as a function of mixture or independent variables.

3. Results and Discussion

3.1. Effect of Mix Parameters on Concrete Slump

Table 6 presents results from laboratory activities obtained from the combination of selected factors influencing concrete performance and their corresponding levels of introduction. The effect of concrete mix parameter on workability such as slump flow (SF) is presented in Figure 2. It was observed that the values of concrete slump flow were significantly affected by the amount of beans pod ash (BPA) and super-plasticizer (SP) dosage present in the mix. Concrete slump flow decreases with corresponding increase in the quantity of BPA and super plasticizer dosage in concrete mix. As the cementitious material increases, the slump flow may improve due to increased lubrication and cohesion; however, if the cementitious material becomes excessively high, it may lead to a decrease in slump flow (JayrajVinodsinhSolanki, 2013). Also, well-graded aggregates with a variety of particle sizes tend to improve slump flow while poorly graded aggregates will reduce concrete slump (Jiao et al., 2017); this was noticed in the corresponding increase in slump flow as fine – total aggregate ratio increases. The least contributing factor is water – cement ratio, being the factor with the lowest rank as presented in Table 7. From Figure 2, the estimated optimum process parameters for obtaining maximum slump value were found to be WC = 0.40, BP = 5%, FT = 0.4 and SP = 6 ml/kg of cement and corresponding level values were as presented and underlined in Table 6 for easy understanding from the response table. This predicted optimum combination is presented in Equation (1).

$$682.50mm = WC_3 + BP_1 + FT_4 + SP_1 \quad (1)$$

Equation 1 implies that with 0.40 of water – cement ratio, 5% replacement of cement with BPA, 0.4 of fine – total aggregate ratio and 600ml of super-plasticizer per 100kg of cement in a 1:2:2 mix, 682.50mm must be achieved as concrete slump value.

Table 5. Quantities of Material Used for BPA – Cement Concrete Specimens

Mix ID	Independent Variables				Material Quantities						
	W-C Ratio	BPA (%)	F-T Agg Ratio	SP Content	Water (ml)	SP (ml)	Cement (kg)	BPA (kg)	Binder (kg)	*FA (kg)	**CA (kg)
M 1	0.3	5	0.25	6	3996	176.2236	28.4715	0.8991	29.3706	35.298	106.6932
M 2	0.3	10	0.3	8	3996	230.1696	26.973	1.7982	28.7712	42.3576	99.58032
M 3	0.3	15	0.35	10	3996	281.718	25.4745	2.6973	28.1718	49.4172	92.46744
M 4	0.3	20	0.4	12	3996	330.8688	23.976	3.5964	27.5724	56.4768	85.35456
M 5	0.35	5	0.3	10	4662	293.706	28.4715	0.8991	29.3706	42.3576	99.58032
M 6	0.35	10	0.25	12	4662	345.2544	26.973	1.7982	28.7712	35.298	106.6932
M 7	0.35	15	0.4	6	4662	169.0308	25.4745	2.6973	28.1718	56.4768	85.35456
M 8	0.35	20	0.35	8	4662	220.5792	23.976	3.5964	27.5724	49.4172	92.46744
M 9	0.4	5	0.35	12	5328	352.4472	28.4715	0.8991	29.3706	49.4172	92.46744
M 10	0.4	10	0.4	10	5328	287.712	26.973	1.7982	28.7712	56.4768	85.35456
M 11	0.4	15	0.25	8	5328	225.3744	25.4745	2.6973	28.1718	35.298	106.6932
M 12	0.4	20	0.3	6	5328	165.4344	23.976	3.5964	27.5724	42.3576	99.58032
M 13	0.45	5	0.4	8	5994	234.9648	28.4715	0.8991	29.3706	56.4768	85.35456
M 14	0.45	10	0.35	6	5994	172.6272	26.973	1.7982	28.7712	49.4172	92.46744
M 15	0.45	15	0.3	12	5994	338.0616	25.4745	2.6973	28.1718	42.3576	99.58032
M 16	0.45	20	0.25	10	5994	275.724	23.976	3.5964	27.5724	35.298	106.6932

**FA – Fine Aggregates; **CA – Coarse Aggregates*

Table 3. Standard L16 Orthogonal Array for Slump Flow and Strengths

Mix ID	Dependent Variables		
	Slump Flow (mm)	Fcu @ 28 Days (N/mm²)	Fy @ 28 Days (N/mm²)
M 1	678	24.80	2.49
M 2	597	22.78	2.29
M 3	586	21.77	2.19
M 4	515	19.12	1.92
M 5	666	24.55	2.46
M 6	566	22.75	2.28
M 7	586	23.18	2.33
M 8	518	19.33	1.94
M 9	648	23.01	2.34
M 10	624	23.89	2.37
M 11	539	21.15	2.13
M 12	573	20.64	2.08
M 13	673	24.01	2.41
M 14	608	24.61	2.48
M 15	518	21.53	2.17
M 16	532	19.21	1.93

Table 7: Response Table for Signal to Noise Ratios of Concrete Slump Flow

Level	W-C Ratio	BPA	F-T Agg	SP
1	55.43	56.47	55.21	55.71
2	55.29	55.54	55.36	55.25
3	55.48	54.91	55.39	55.56
4	55.26	54.55	55.51	54.95
Delta	0.22	1.92	0.31	0.75
Rank	4	1	3	2

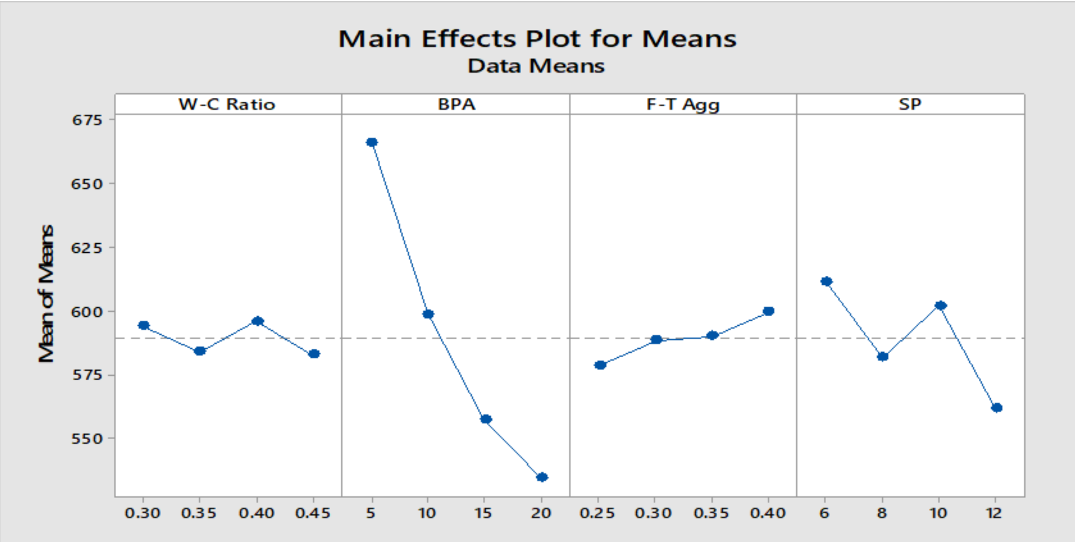

Figure 2. Effect of Mixture Parameter on Concrete Slump Flow

3.2. Effect of Mix Parameters on Concrete Strength

The effect of concrete mix parameter on the compressive and split tensile strength of concrete is as shown in Figure 3 and Figure 4. It was observed that the values of both compressive and split tensile strength of concrete were significantly influenced by the quantity of BPA and SP dosage present in the mix. Compressive strength, likewise split tensile strength decreases with corresponding increase in the amount of BPA and SP dosage in the concrete mix. The reduction in concrete strength being experienced as a result of poor cementitious properties of pozzolans may be due to the presence of impurities in them. The impurities interfere with the hydration process and hinder the development of the desired strength (Ismail *et al.,* 2020). Also, inadequate pozzolanic activity and variability in ash composition may be responsible for the trend of this nature (Sharma and Sivapullaiah, 2016). Likewise, the reduction in concrete strength experienced with corresponding increase in SP dosage beyond the optimal range may be due to excessive fluidity caused by excessive dosage of SP in the mix (Sathyan et al., 2018). This excessive fluidity weakens the concrete and result in reduced compressive and split tensile strength (Ayanlere et al., 2023). The parameter with the lowest rank in Table 8 and Table 9 reveals that water – cement (WC) ratio is the least contributing factor to the concrete strength performance. The estimated optimum process parameters for obtaining maximum compressive strength using Taguchi method were found at WC = 0.35, BP = 5%, FT = 0.4 and SP = 6 ml/kg of cement and corresponding level values were underlined in Table 8 for easy understanding of the response table. The predicted optimum combination is presented in Equation 2.

$$25.44N/mm^2 = WC_2 + BP_1 + FT_4 + SP_1 \qquad (2)$$

Likewise, the estimated optimum process parameters for obtaining maximum split tensile strength was obtained at WC = 0.35, BP = 5%, FT = 0.4 and SP = 6 ml/kg of cement. The predicted optimum combination is presented in Equation 3.

$$2.55N/mm^2 = WC_2 + BP_1 + FT_4 + SP_1 \qquad (3)$$

Equation 2 and Equation 3 imply that with 0.35 water – cement ratio, 5% replacement of cement with BPA, 0.4 of fine – total aggregate ratio and 600ml of super-plasticizer per 100kg of cement in a 1:2:2 mix, 25.44N/mm^2 and 2.55N/mm^2 must be achieved for compressive and split tensile strength respectively.

Table 8. Response Table for Signal to Noise Ratios of Concrete Compressive Strength

Level	W-C Ratio	BPA	F-T Agg	SP
1	26.86	27.63	26.80	27.33
2	26.99	27.42	26.98	26.75
3	26.90	26.81	26.89	26.95
4	26.94	25.83	27.03	26.67
Delta	0.14	1.80	0.22	0.66
Rank	4	1	3	2

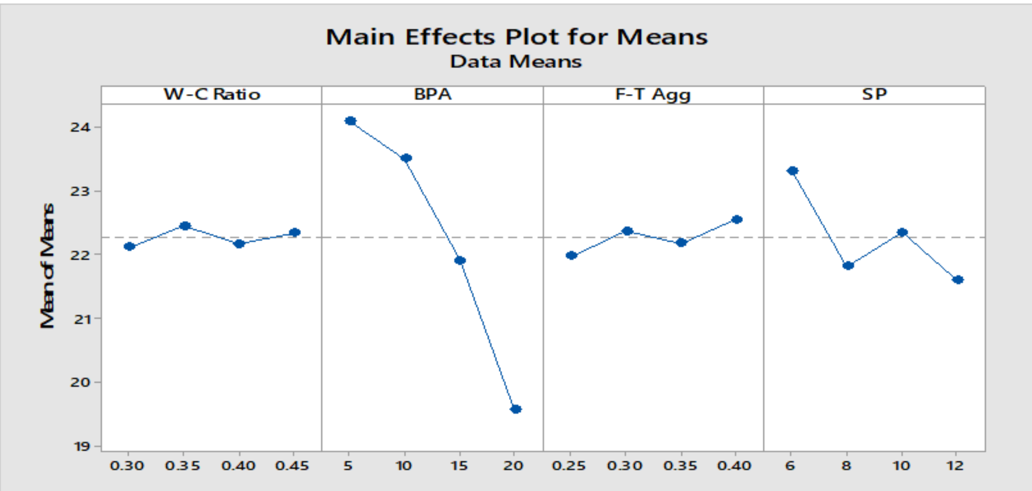

Figure 3. Effect of Mixture Parameter on Compressive Strength of Concrete.

Table 9. Response Table for Signal to Noise Ratios of Concrete Split Tensile Strength

Level	W-C Ratio	BPA	F-T Agg	SP
1	6.899	7.692	6.840	7.380
2	7.020	7.435	7.026	6.790
3	6.952	6.863	6.960	6.958
4	6.992	5.874	7.037	6.735
Delta	0.121	1.818	0.197	0.646
Rank	4	1	3	2

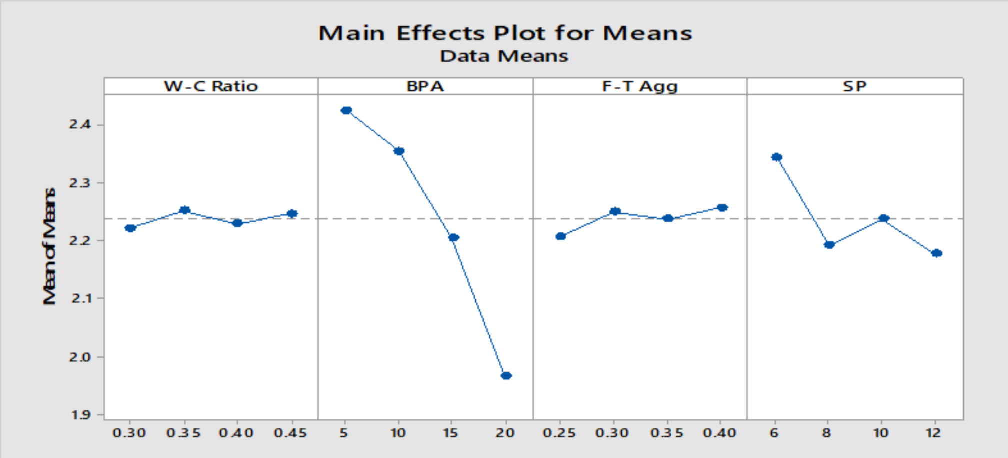

Figure 4. Effect of Mixture Parameter on Split Tensile Strength of Concrete

4. Conclusions

The study showed that the most influencing factors affecting concrete slump flow, compressive and split tensile strengths are the quantity of beans pod ash and super-plasticizer dosage available in the concrete mix while the least influencing factor is water – cement ratio. Concrete compressive strength was noticed to change significantly from 25.44N/mm^2 to 20.90N/mm^2 when the quantity of BPA was altered from 5% to 20%, giving the largest difference of 4.54N/mm^2 experienced in the various parameters changes. These most influencing parameters are the parameters that give the highest difference between the smallest and largest performance values; while the parameters that give the least difference is termed as the least influencing parameter, because changes in the quantity of the factor does not alter the performance value.

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