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Utilization of Industrial Byproducts in Concrete Applications by Adopting Grey Taguchi Method for Optimization

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Abstract**—**This paper presents the results of an experimental investigation carried out to evaluate the effects of partial replacement of cement and fine aggregate with industrial waste byproducts on concrete strength properties. The Grey Taguchi approach has been used to optimize the mix proportions for desired properties. In this research work, a ternary combination of industrial waste byproducts has been used. The experiments have been designed using Taguchi's L9 orthogonal array with four factors having three levels each. The cement was partially replaced by ladle furnace slag (LFS), fly ash (FA) and copper slag (CS) at 10%, 25% and 40% level and fine aggregate (sand) was partially replaced with electric arc furnace slag (EAFS), iron slag (IS) and glass powder (GP) at 20%, 30% and 40% level. Three water to binder ratios, fixed at 0.40, 0.44 and 0.48, were used, and the curing age was fixed at 7, 28 and 90 days. Thus, a series of nine experiments was conducted on the specimens for water to binder ratios of 0.40, 0.44 and 0.48 at 7, 28 and 90 days of the water curing regime. It is evident from the investigations that Grey Taguchi approach for optimization helps in identifying the factors affecting the final outcomes, i.e. compressive strength and split tensile strength of concrete. For the materials and a range of parameters used in this research, the present study has established optimum mixes in terms of strength properties. The best possible levels of mix proportions were determined for maximization through compressive and splitting tensile strength. To verify the results, the optimal mix was produced and tested. The mixture results in higher compressive strength and split tensile strength than other mixes. The compressive strength and split tensile strength of optimal mixtures are also compared with the control concrete mixtures. The results show that compressive strength and split tensile strength of concrete made with partial replacement of cement and fine aggregate is more than control concrete at all ages and w/c ratios. Based on the overall observations, it can be recommended that industrial waste byproducts in ternary combinations can effectively be utilized as partial replacements of cement and fine aggregates in all concrete applications.

Keywords**—**Analysis of variance, ANOVA, compressive strength, concrete, grey Taguchi method, industrial byproducts, split tensile strength.

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I. INTRODUCTION

TODAY, concrete is one of the most widely used construction materials in the world. Concrete has many advantages such as flexibility in shaping, high compressive strength, durability, fire resistance and ease of production and finally, less cost of production over other construction materials. In today's construction scenario, there is an acute shortage of cement as well as the fine aggregate (sand). It is estimated that 5 billion metric tons of cement would be produced by 2030 throughout the world [1]. The vast applications of Ordinary Portland Cement (OPC) in concrete and the growing demand of OPC in the future will also create some major environmental issues such as reduced availability of raw material, increased CO_2 emissions and need for large input of energy during manufacturing of OPC. It is a well-known fact that during the production of one ton of OPC approximately one ton of CO_2 is emitted into the atmosphere. The cement industry is responsible for about 7% of all the CO_2 emissions into the atmosphere, and it is estimated that by the year 2020, the CO_2 emissions will rise by about 50% from the current levels. The cement production accounts for about 5% of worldwide industrial energy consumption and for producing each ton of OPC, about 1.5 tons of raw material is needed [45].

The problems of OPC concrete mentioned above have motivated the researchers to consider alternative materials that are environmentally friendly and provide sustainable development in concrete production. The appropriate strength required, the reduction of energy and the natural resources consumed and minimal environmental effect have encouraged the researchers to consider alternative concrete manufacturing that contains other ingredients such as industrial byproducts. Likewise cement, aggregates makeup 70% of concrete volume and is the principal material in concrete production and consumes globally 8-12 million tons of natural aggregates annually [2]. Sand is usually a major component of the mix than cement. The growing demand for sand results in non-availability of good quality sand especially in India. The existing natural sand deposits are being consumed rapidly, which is an extreme environmental problem. As such, finding an alternative material to cement and natural sand has become very imperative. As the industrialization increases, the amount of waste material/byproducts like slags is also increasing, which has turned into an ecological issue that must be managed. Slags have a variable composition depending on the raw materials and the industrial process; hence, the effect that an activator can have on strength may be different for slags of different origins, and each slag responds differently to the activation. Therefore, it is necessary to determine the most suitable and optimum composition for each case.

With ever-increasing quantity of industrial byproducts and waste materials being produced regularly, solid waste management has become the principal environmental concern in the world. The scarcity of land-filling space and its ever-increasing cost, utilizing/recycling byproducts/waste has become an attractive alternative to mere disposal. The use of these materials makes the concrete economical and in addition, helps in resolving their disposal problems. Using varied industrial byproducts individually or in combination as a partial replacement in concrete has been accepted by many codes worldwide. Several studies have been carried out to investigate the synergic effect of using ternary blends containing different supplementary cementitious materials (SCMs) in concrete [3], [4]. The shortcomings of individual SCMs in meeting multiple and often conflicting demands of concrete properties can be overcome by using combinations of two or more SCMs. In the majority of the studies, the ternary blends of SCMs have exhibited superior performance compared to binary blends, in terms of the rheological, mechanical and the durability properties of concrete [46]-[48]. The use of design of experiments in utilizing the byproducts in proportioning concrete mixes is certainly the need of the hour. This study is a step towards scientifically applying the experimental design along with Grey Relational Analysis (GRA) for concrete mix proportioning incorporating the various industrial byproducts in ternary combinations both as partial replacement of cement as well as fine aggregate.

The main objective of this study is to find the optimal use of some industrial byproducts such as FA, LFS, CS, EAFS, IS and GP as substitutes to cement and fine aggregates in ternary combinations as well as to investigate the effect of these industrial byproducts on the compressive strength and split tensile strength of concrete. In this study, the cement was partially replaced by FA, LFS and CS using 10%, 25% and 40% replacement levels. The fine aggregate was partially replaced by EAFS, IS and GP at 20%, 30% and 40% replacement levels. The experiment plan was designed using Taguchi's L_9 orthogonal array varying four factors at three levels each. In the present work, four factors namely (i) type of replacement as binder i.e. FA, LFS and CS, (ii) type of replacement as fine aggregate i.e. EAFS, IS and GP, (iii) percentage of byproduct to be used as partial replacement of cement i.e. 10%, 25% and 40% and (iv) percentage of byproduct to be used as partial replacement of fine aggregate i.e. 20%, 30% and 40% were considered to evaluate their effect on compressive and split tensile strengths.

A. Research Significance in Indian Context

The availability of cement and good quality aggregates is depleting day-by-day due to tremendous growth in the Indian construction industry. So, for the manufacturing of cement concrete, we require large volumes of cement and aggregates for fulfilling the demand of the construction industry. In order to fulfill the future demand for cement and aggregates, we will have to identify potential alternative replacement materials for cement and aggregates to fulfill the future growth aspiration of the Indian construction industry. Use of various industrial byproducts such as FA, LFS, CS, EAFS, IS and GP provides a great opportunity to utilize these waste materials as an alternative to normally available cement and aggregates. The total steel production in India is about 95.60 million tones, and the waste generated annually is around 20 million tones (considerably higher than the world average), but hardly 25% is being used mostly in cement production [5].

II. Literature Review

The usage of mineral admixtures such as FA, LFS, CS, EAFS, IS and GP play a major role in improving the engineering properties and performance of concrete mix design [6]. Many studies have been carried out for predicting the strength of concrete when mixed with industrial byproducts/waste both as replacement of cement as well as fine/coarse aggregate in binary combinations [49]-[51]. However, very few studies have used industrial byproducts/ waste in ternary combinations [46]-[48]. Due to the synergic effect of using ternary blends containing different SCMs in concrete, they have exhibited superior performance compared to binary blends in terms of rheological, mechanical and durability properties of concrete [3], [4]. Gesoglu et al. [7] studied the effect of using SCMs in binary, ternary, and quaternary blends on the hardened properties of self-compacting concrete (SCC). The control mixture contained only Portland cement (PC) as the binder while the remaining mixtures incorporated binary, ternary, and quaternary cementitious blends of PC, FA, Granulated Blast Furnace Slag (GGBFS) and Silica Fume (SF). Test results found that incorporating the mineral admixtures improve the compressive strength of concretes made with SF and GGBFS. Adolfsson et al. [8] investigated the hydraulic characteristics of LFS as a substitute of cement for some applications. Manso et al. [9] examined the properties of masonry mortars made with LFS and showed that the presence of LFS does not damage and rather may even contribute to increasing mortar durability. Papayianni et al. [10] used high-calcium fly ash and LFS as a binder and EAFS as aggregate. The produced concrete showed high-strength (>70 MPa) by substituting 100% of the coarse and 50% of the fine aggregate by EAF. Rodriguez et al. [11] discussed the attractive option of using LFS in the manufacture of masonry mortars and found the improvements in the properties of the mortars and considerable savings in use of cement and sand by using LFS. Setien et al. [12] presented the data characterizations of several kinds of LFS, setting out referential values for their use in construction applications. Pellegrino et al. [13] undertook a study to investigate the opportunity to substitute natural aggregates of traditional concrete with Black/Oxidizing EAF slag and found that the 28-day compressive strength increased 30% as opposed to natural aggregate concrete. Maslehuddin et al. [14] conducted a study to evaluate the mechanical properties and durability characteristics of cement-concrete specimens prepared with electric arc furnace dust (EAFD). Siddique [15] presented the results of an experimental investigation dealing with concrete incorporating high volumes of Class F FA. Nochaiya et al. [16] reported the normal consistency, setting time, workability and compressive strength results of cement–FA– SF concrete systems. Chidiac et al. [17] studied the use of GP in high strength concrete. Taha et al. [18] studied the influence of lithium nitrate and pozzolanic glass powder (PGP) on the expansion induced by the alkali-silica reaction (ASR). Shayan et al. [19], [20] used fine glass powder for incorporation into concrete as a pozzolanic material. Liu [21] investigated the feasibility of using ground glass in SCC, whereas, Limbachiya [22] examined the performance of Portland-cement concrete produced with washed glass sand (WGS). Schwarz et al. [23] investigated the influence of a GLP on cement hydration. Qasrawi et al. [24] found that the compressive strength of concrete using steel slag as a fine aggregate was 1.1-1.3 times the common concrete. Ducman et al. [25] investigated the feasibility of the refractory concrete production using EAFS as aggregate and the results showed that when slag was heated up to a temperature of 1000 °C prior to its use for refractory concrete, the final products exhibited mechanical properties which are comparable to concrete with conventional refractory aggregate, e.g. bauxite. Corinaldesi et al. [26] reported that no ASR expansion had been detected with particle size up to 100 μm of glass particles that partially replaced natural sand at levels of 30% and 70%, by weight, thus reflecting the feasibility of waste glass reuse as fine aggregate in concrete. Rashad [27] reviewed from several studies that the ASR expansion of mortar and concrete specimens containing glass sand can be mitigated by adding 10–30% Metakaoline (MK), 20–50% FA, 50–60% slag, 10% SF, 1–2% Ni_2CO_3, 1% $LiNO_3$ and suitable amount of fibers. Kourounis et al. [35] reported that steel slag have cementitious properties due to the presence of C_3S, C_2S and C_4AF. Huang et al. [29] prepared a cementitious material by utilizing phosphogypsum (PG), steel slag (SS), GGBFS and limestone (LS). The results showed that the 28 days compressive strength of a mixture of 45% PG, 10% SS, 35% GGBFS and 10% LS exceeded 40 MPa and the main hydration products were ettringite and C–S–H gel. Chen et al. [30] observed a significant improvement in the compressive strength of waste E-glass (size <75 μm) concrete mixtures at late ages. The compressive strength of specimens with 40% E-glass content by weight was 17%, 27% and 43% higher than that of the control specimen at the ages of 28, 91 and 365 days, respectively. The particle size of 75 μm passed the strength requirement of pozzolanic materials as proposed by Shao et al. [31]. Tixieret et al. [32] studied the effect of CS on the mechanical properties of cementitious mixtures as cement replacement and found that CS significantly increases the compressive strength of concrete mixtures due to densification of the microstructure in the capillary pore region. Pellegrino et al. [33] found that replacement of fine natural aggregates with EAF slag is feasible at lower substitution ratios only. Thomas [34] in his review paper stated that ASR damages could be effectively mitigated by using FA and other SCMs in concrete. Adaway et al. [35] replaced fine aggregate with GP at 15, 20, 25, 30 and 40% level. There was a 30% increase of compressive strength than the control concrete strength. Kothai et al. [36] found that there was increase in the compressive strength of the concrete and the optimum value obtained was 30% of the slag as fine aggregate replacement. It was also observed that with the further replacement of slag with fine aggregate decreases the compressive strength. Thus, on the basis of the reviewed literature, it can be derived that all the SCM's considered in the present study could be used as effective partial replacement materials in the concrete matrix.

III. Design of Experiments

Taguchi's method of experimental design provides a simple, efficient, and systematic approach for the optimization of experimental designs for performance quality and cost [37]. To evaluate each independent factor or their interaction effects on the process characteristics, Taguchi used standard orthogonal arrays (OA). In this study, the goal was to maximize the compressive strength and split tensile strength of concrete.

With the considered goal in mind, four control factors (parameters), i.e., (1) percentage of byproduct to be used as partial replacement of cement, (2) percentage of byproduct to be used as partial replacement of fine aggregate, (3) type of replacement as binder and (4) type of replacement as Fine aggregate labeled as A, B, C and D respectively, were varied at three levels. Table I shows the control factors and their respective levels.

Four control factors and their three levels were selected after reviewing the relevant literature on the subject. The choice of three levels of each control factor has also been made keeping in view the nonlinear effect of these control factors on the performance characteristics of concrete.

When the design type is full factorial, it is necessary to conduct $81(3^4)$ experiments because all the possible combinations should be introduced in the design. To reduce the number of tests, an L9 standard OA that only needs 9 experimental runs is adopted. The L9 standard OA, as suggested by Taguchi for four parameters at three levels, is given in Table II. The detail of 9 trial mixtures based on the standard OA is shown in Table III.

TABLE I
The Considered Levels for Each Parameter in Taguchi Design of Experiment

Parameters/control factors	Level 1	Level 2	Level 3
A) Percentage of byproduct to be used as partial replacement of cement	10%	25%	40%
B)Percentage of byproduct to be used as partial replacement of fine aggregate	20%	30%	40%
C) Type of replacement as a binder	FA	LFS	CS
D)Type of replacement as fine aggregate	EAFS	IS	GP

IV. Experimental Study

A. Characterization of Materials

The physical and chemical characteristics of the materials used in the experimental study are discussed in the following sub-sections.

TABLE II
L9 STANDARD OA SUGGESTED BY TAGUCHI FOR 4 PARAMETERS AT 3 LEVELS

Experiment series	Parameter/ factor A	Parameter/ factor B	Parameter/ factor C	Parameter/ factor D
	Levels			
T1	1	1	1	1
T2	1	2	2	2
T3	1	3	3	3
T4	2	1	2	3
T5	2	2	3	1
T6	2	3	1	2
T7	3	1	3	2
T8	3	2	1	3
T9	3	3	2	1

TABLE III
DETAIL OF TRIAL MIXTURES

Trial mixture	A). Percentage of byproduct to be used as partial replacement of cement	B). Percentage of byproduct to be used as partial replacement of fine aggregate	C). Type of replacement as a binder	D). Type of replacement as fine aggregate
T1	10%	20%	FA	EAFS
T2	10%	30%	LFS	Iron Slag
T3	10%	40%	CS	GP
T4	25%	20%	LFS	GP
T5	25%	30%	CS	EAFS
T6	25%	40%	FA	Iron Slag
T7	40%	20%	CS	Iron Slag
T8	40%	30%	FA	GP
T9	40%	40%	LFS	EAFS

1. Cement

The OPC of 43 grade used in this study fulfilled the requirements of BIS:8112-1989 [38]. The chemical composition, fineness, setting times, consistency and compressive strength of cement used in this study are given in Table IV.

TABLE IV
PHYSICAL PROPERTIES OF CEMENT

S. No.	Characteristic	The value obtained in the laboratory
1.	Specific gravity	3.12
2.	Fineness (% retained on 90 µm Sieve)	2
3.	Standard consistency (%)	27.5
4.	Initial setting time (minutes)	125
5.	Final setting time (minutes)	170
6.	Compressive strength (MPa)	3 days = 31.5 7 days = 40.5 28 days = 47.0

2. Fine Aggregate

The fine aggregate/sand used in the experimental program was locally procured and confirmed to zone-II as per Indian standard specification BIS: 383-1970 [39]. The physical properties of fine aggregate used are given in Table V.

3. Coarse Aggregate

Locally available coarse aggregates were used in the present study. The physical properties of 20 mm and 10 mm aggregates, as determined in the laboratory, are given in Table VI. The aggregates satisfied the requirements as per Indian standard specification BIS: 383-1970 [39].

TABLE V
PHYSICAL PROPERTIES OF FINE AGGREGATE

S. No.	Characteristic	Value obtained in the laboratory
1.	Specific gravity	2.73
2.	Fineness Modulus	2.46
3.	Water absorption	1.01%
4.	Grading Zone	II

TABLE VI
PHYSICAL PROPERTIES OF COARSE AGGREGATE

S. No.	Characteristic	Value obtained in the laboratory (10 mm)	Value obtained in the laboratory (20 mm)
1.	Specific gravity	2.72	2.69
2.	Fineness Modulus	6.42	7.05
3.	Water absorption	0.8%	0.20%

4. Industrial Byproducts

The industrial byproducts such as FA, LFS, CS, GP, IS and EAFS used in this study were obtained from nearby industries. The chemical properties of these byproducts were obtained using energy dispersive X-ray spectroscopy (EDAX) and scanning electron microscopy (SEM). The physical properties and chemical composition of these byproducts used as a binder and fine aggregates are given in Tables VII and VIII, respectively.

TABLE VII
PHYSICAL PROPERTIES AND CHEMICAL COMPOSITION OF BYPRODUCTS USED AS A BINDER BY SEM AND EDAX

CS		LFS		FA	
Fineness (% retained on 90 µm sieve)	15	Fineness (% retained on 90 µm sieve)	10	Fineness (% retained on 90 µm sieve)	0
Specific gravity	3.91	Specific gravity	3.35	Specific gravity	2.35
CaO	1.12%	CaO	51.33%	CaO	0.89%
SiO_2	12.27%	SiO_2	13.98%	SiO_2	49.65%
Al_2O_3	1.65%	Al_2O_3	6.21%	Al_2O_3	35.52%
FeO	76.66%	MgO	1.61%	FeO	6.72%
CuO	0.83%	CuO	1.31%	CuO	2.43%
SO_3	0.73%	SO_3	4.09%	SO_3	---
K_2O	0.28%	K_2O	---	K_2O	1.09%
ZnO	2.23%	ZnO	---	ZnO	2.14%
CO_2	4.23%	CO_2	21.46%	TiO_2	1.55%

3. Superplasticizer

The superplasticizer used in the study was polycarboxylate based superplasticizer, i.e. Auramix 400 which conforms to BIS: 9103-1999 [40]. Auramix 400 is used in the concrete production where both high water reduction and workability retention is required for longer periods. The properties of the superplasticizer are given in Table IX.

B. Mix Proportions

The control concrete mix proportions were designed for w/c ratios of 0.48, 0.44 and 0.40 having a slump of 50-75 mm as per BIS: 10262-2009 [48] method of mix design and are shown in Table X.

Tables XI-XIII provide the mix proportion details for mixes with replacements considering the specific gravity of byproducts for w/b ratios of 0.40, 0.44 and 0.48, respectively. Super-plasticizer was added to the concrete mix in order to keep the workability between 50-75 mm slump value.

TABLE VIII
PHYSICAL PROPERTIES AND CHEMICAL COMPOSITION OF BYPRODUCTS USED AS A FINE AGGREGATE BY SEM AND EDAX

GP		EAFS		IS	
Fineness (% retained on 90 µm sieve)	0.50	Fineness (% retained on 90 µm sieve)	36	Fineness (% retained on 90 µm sieve)	82
Specific gravity	2.61	Specific gravity	2.93	Specific gravity	3.35
CaO	3.89%	CaO	29.92%	CaO	0.85%
SiO_2	53.42%	SiO_2	4.33%	SiO_2	30.33%
Al_2O_3	2.11%	Al_2O_3	24.09%	Al_2O_3	12.40%
MgO	1.86%	MgO	13.45%	MgO	0.75%
CO_2	5.77%	CO_2	17.46%	CO_2	34.95%
K_2O	7.41%	$\sum TiO_2 + SO_3 + MnO + Cr_2O_3$	---	TiO_2	0.60%
Na_2O	6.32%	PiO_2	10.76%	MnO	9.67%
PbO	15.84%			FeO	10.45%
CuO	3.38%			CuO	----

C. Test Setup

Casting and Testing

A set of three 150 mm cubes were cast for each trial mix and for each w/b ratio of 0.48, 0.44 and 0.40 for determining the compressive strength at curing ages of 7, 28 and 90 days, respectively. Similarly, 150 mm x 300 mm cylinders (set of three) were cast for each trial mix and for each w/b ratio of 0.48, 0.44 and 0.40 for determining the split tensile strength at 7, 28 and 90 days of curing age. All the specimens were de-molded after 24±1 h of adding water to the concrete mixture and thereafter were put into the water tank for curing maintaining the temperature at 27 ± 2 °C as per IS requirements up to the specified age of the test.

TABLE IX
PROPERTIES OF SUPERPLASTICIZER

S. No.	Characteristics	Value
1.	Appearance	Light yellow colored liquid
2.	pH	6.0
3.	Chloride content	Nil
4.	Volumetric mass @ 200 C	1.09 Kg/litre
5.	Alkali content	Less than 1.5 g Na_2 equivalent/litre of admixture

TABLE X
MIX PROPORTIONS OF CONTROL CONCRETE

Mix	w/b ratio	Water (Kg/m³)	Cement (Binder) (Kg/m³)	Sand (Kg/m³)	CA1(20) (Kg/m³)	CA2(10) (Kg/m³)
MD1S	0.48	178	370.83	701.23	768.28	382.63
MD2S	0.44	176	400.00	678.93	769.76	383.36
MD3S	0.40	175	437.5	653.34	766.80	381.88

TABLE XI
CONCRETE MIX DESIGN PROPORTIONS USING SPECIFIC GRAVITY OF BYPRODUCTS (W/B= 0.40)

Exp. No	Water (Kg/m³)	Binder (Kg/m³)			Fine aggregate (Kg/m³)			Coarse aggregate (20 mm) (Kg/m³)	Coarse aggregate (10 mm) (Kg/m³)	Super-plasticizer (l/m³)
		Cement	Replacement material (%)	Amount	Sand	Replacement material (%)	Amount			
T1	175	393.75	FA(10)	32.95	522.67	EAFS(20)	140.24	766.8	381.88	1.97
T2	175	393.75	LFS(10)	46.97	457.33	IS(30)	240.51	766.8	381.88	2.95
T3	175	393.75	CS(10)	54.83	392	GP(40)	249.85	766.8	381.88	3.93
T4	175	328.12	LFS(25)	117.44	522.67	GP(20)	124.92	766.8	381.88	3.28
T5	175	328.12	CS(25)	137.07	457.33	EAF(30)	210.36	766.8	381.88	3.28
T6	175	328.12	FA(25)	82.38	392	IS(40)	320.68	766.8	381.88	3.28
T7	175	262.5	CS(40)	219.31	522.67	IS(20)	160.33	766.8	381.88	1.31
T8	175	262.5	FA(40)	131.81	457.33	GP(30)	187.39	766.8	381.88	2.62
T9	175	262.5	LFS(40)	187.90	392	EAF(40)	280.47	766.8	381.88	5.24

TABLE XII
CONCRETE MIX DESIGN PROPORTIONS USING SPECIFIC GRAVITY OF BYPRODUCTS (W/B= 0.44)

Exp. No	Water (Kg/m³)	Binder (Kg/m³)			Fine aggregate (Kg/m³)			Coarse aggregate (20 mm) (Kg/m³)	Coarse aggregate (10 mm) (Kg/m³)	Super-plasticizer (l/m³)
		Cement	Replacement material (%)	Amount	Sand	Replacement material (%)	Amount			
T1	176	360	FA(10)	30.13	543.14	EAF(20)	145.73	769.76	383.36	0.9
T2	176	360	LFS(10)	42.95	475.25	IS(30)	249.93	769.76	383.36	2.16
T3	176	360	CS(10)	50.13	407.36	GP(40)	259.63	769.76	383.36	2.7
T4	176	300	LFS(25)	107.37	543.14	GP(20)	129.82	769.76	383.36	2.25
T5	176	300	CS(25)	125.32	475.25	EAF(30)	218.6	769.76	383.36	2.25
T6	176	300	FA(25)	75.32	407.36	IS(40)	333.24	769.76	383.36	1.5
T7	176	240	CS(40)	200.51	543.14	IS(20)	166.62	769.76	383.36	0.72
T8	176	240	FA(40)	120.52	475.25	GP(30)	194.73	769.76	383.36	1.2
T9	176	240	LFS(40)	171.80	407.36	EAF(40)	291.47	769.76	383.36	4.8

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TABLE XIII
CONCRETE MIX DESIGN PROPORTIONS USING SPECIFIC GRAVITY OF BYPRODUCTS (W/B= 0.48)

Exp. No	Water (Kg/m³)	Binder (Kg/m³)			Fine aggregate(Kg/m³)			Coarse aggregate (20 mm) (Kg/m³)	Coarse aggregate 9 (10 mm) (Kg/m³)	Super-plasticizer (l/m³)
		Cement	Replacement material (%)	Amount	Sand	Replacement material (%)	Amount			
T1	178	333.75	FA(10)	27.93	560.98	EAF(20)	150.52	768.28	382.63	0.33
T2	178	333.75	LFS(10)	39.82	490.86	IS(30)	258.14	768.28	382.63	1.66
T3	178	333.75	CS(10)	46.47	420.74	GP(40)	267.13	768.28	382.63	1.66
T4	178	278.12	LFS(25)	99.54	560.98	GP(20)	133.56	768.28	382.63	1.39
T5	178	278.12	CS(25)	116.18	490.86	EAF(30)	225.78	768.28	382.63	1.39
T6	178	278.12	FA(25)	69.83	420.74	IS(40)	344.19	768.28	382.63	0.69
T7	178	222.5	CS(40)	185.90	560.98	IS(20)	172.1	768.28	382.63	0.44
T8	178	222.5	FA(40)	111.73	490.86	GP(30)	200.35	768.28	382.63	1.1
T9	178	222.5	LFS(40)	159.27	420.74	EAF(40)	301.04	768.28	382.63	4.44

TABLE XIV
COMPRESSIVE AND SPLIT TENSILE STRENGTH OF THE CONTROL CONCRETE MIX

S. No.	Mix designation	w/c ratio	Compressive strength (MPa)			Split tensile strength (MPa)		
			7-days	28-days	90-days	7-days	28-days	90-days
1	MD1S	0.48	27.00	42.06	46.20	2.21	3.45	3.81
2	MD2S	0.44	30.50	45.13	47.20	2.40	3.82	4.21
3	MD3S	0.40	39.80	51.05	55.64	2.97	4.47	4.89

TABLE XV
COMPRESSIVE AND SPLIT TENSILE STRENGTHS OF TRIAL MIXES AT W/B=0.48

Trial mix	Combination	Compressive strength (MPa)			Split tensile strength (MPa)		
		7-days	28-days	90-days	7-days	28-days	90-days
T1	A1B1C1D1	28.60	46.05	57.09	2.13	3.15	3.68
T2	A1B2C2D2	28.38	45.02	55.96	1.96	3.03	3.25
T3	A1B3C3D3	26.48	39.82	45.98	1.85	2.90	3.31
T4	A2B1C2D3	21.48	30.23	38.50	1.72	2.68	3.20
T5	A2B2C3D3	22.30	33.96	41.09	1.89	2.89	3.31
T6	A2B3C1D2	22.73	39.08	56.77	2.34	3.00	3.47
T7	A3B1C3D2	16.06	23.76	31.10	1.17	1.88	2.79
T8	A3B2C1D3	21.78	31.82	44.73	1.63	2.63	3.38
T9	A3B3C2D1	17.16	24.11	32.45	1.60	2.33	2.53

TABLE XVI
COMPRESSIVE AND SPLIT TENSILE STRENGTHS OF TRIAL MIXES AT W/B=0.44

Trial mix	Combination	Compressive strength (MPa)			Split tensile strength (MPa)		
		7-days	28-days	90-days	7-days	28-days	90-days
T1	A1B1C1D1	30.97	47.83	61.33	2.53	3.36	3.76
T2	A1B2C2D2	31.00	45.68	56.21	2.22	3.12	3.45
T3	A1B3C3D3	29.83	40.79	48.11	2.15	2.98	3.39
T4	A2B1C2D3	26.94	37.14	43.45	1.78	2.74	3.26
T5	A2B2C3D3	28.82	37.62	45.34	2.00	3.04	3.67
T6	A2B3C1D2	30.42	46.60	60.35	2.55	3.10	3.75
T7	A3B1C3D2	19.58	27.03	33.81	1.94	2.33	2.83
T8	A3B2C1D3	25.74	37.95	51.62	1.97	3.05	3.66
T9	A3B3C2D1	23.96	28.08	36.74	1.76	2.59	2.71

TABLE XVII
COMPRESSIVE AND SPLIT TENSILE STRENGTHS OF TRIAL MIXES AT W/B=0.40

Trial mix	Combination	Compressive strength (MPa)			Split tensile strength (MPa)		
		7-days	28-days	90-days	7-days	28-days	90-days
T1	A1B1C1D1	41.50	53.76	72.05	2.67	3.41	4.58
T2	A1B2C2D2	39.82	50.32	64.35	2.47	3.24	4.07
T3	A1B3C3D3	30.80	46.20	51.18	2.23	3.10	3.57
T4	A2B1C2D3	27.50	39.60	44.55	2.21	2.82	3.46
T5	A2B2C3D3	29.81	40.92	46.20	2.42	3.20	3.87
T6	A2B3C1D2	31.24	49.94	66.33	2.64	3.25	4.00
T7	A3B1C3D2	21.12	31.21	36.22	2.06	2.55	3.15
T8	A3B2C1D3	29.77	49.14	64.90	2.03	3.41	3.80
T9	A3B3C2D1	25.85	30.88	39.38	2.20	2.69	2.76

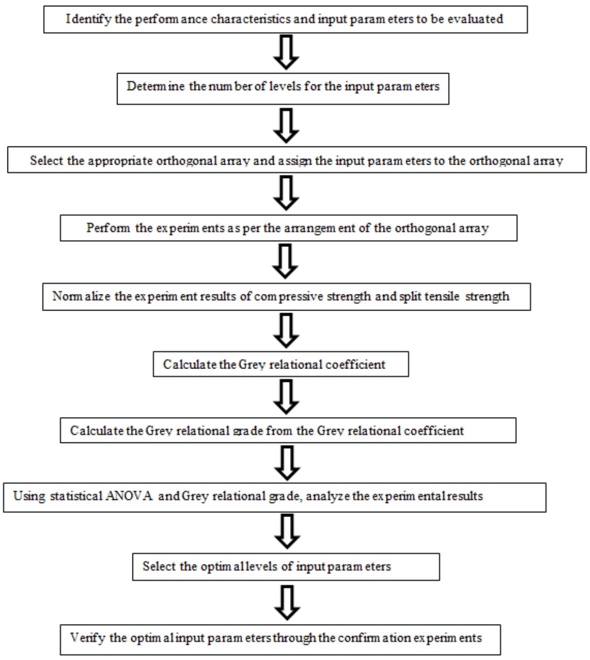

Fig. 1 Steps followed in Grey relational analysis with Taguchi method

1. Hardened Concrete Properties

For each concrete mix, the set of 150 mm cubes (3 Nos.) was tested for compressive strength at 7, 28, and 90 days curing age as per BIS:516-1959 [42]. Similarly, 150 x 300 mm cylinders were tested for split tensile strength at 7, 28, and 90 days curing age as per the BIS:5816-1999 [43]. The compressive and split tensile strengths of the control concrete mix are shown in Table XIV. The compressive and split tensile strength of trial mixes incorporating the designated partial replacement materials, at w/b ratios of 0.48, 0.44 and 0.40 are shown in Tables XV-XVII.

V. GRA

GRA was proposed by Deng [44] and is widely applied by many researchers to optimize control parameters which are having multi-responses by grey relational grade. The following steps are followed to optimize the input parameters with multiple performance characteristics or output responses using GRA with Taguchi method as shown in Fig. 1.

The nine sets of experiments were carried out for each w/b ratios, i.e. 0.48, 0.44 and 0.40 and for each curing period of 7, 28 and 90 days, however, the detailed calculations for one set of nine experiments, i.e. for w/b=0.40 and curing period of 90 days has only been presented here. The optimal parameters are found with these detailed calculations. The optimal parameters for all other combinations of experiments for w/b ratios and curing periods are presented in Table XXIV. Table XVIII shows the experimental layout and performance results for w/b=0.40 and for curing period of 90 days. In this method, the multiple performance characteristics can be converted into a single grey relational grade. The following are the stages involved in the approach.

A. Data Pre-Processing/Normalization

In GRA, the data pre-processing is the first step to normalize the random grey data with different measurement units, to transform them into dimensionless parameters. Thus, data pre-processing converts the original sequences to a set of comparable sequences. Different methods are employed to pre-process the grey data depending upon the quality characteristics of the original data. As we know that the compressive strength (CS) and split tensile strength (STS) are "larger-the-better" characteristics of concrete, the original sequence was normalized by using (1):

$$X_i^*(k) = \frac{X_i(k) - minX_i(k)}{maxX_i(k) - minX_i(k)} \quad (1)$$

where, $X_i(k)$ and $X_i^*(k)$ are the comparability sequence and sequence after the data preprocessing respectively, and k=1 and 2 for CS and STS, respectively; i=1, 2, 3…... 9 for experiment numbers 1 to 9. All the sequences after data pre-processing using (1) are presented in Table XIX.

TABLE XVIII
EXPERIMENTAL LAYOUT USING L9 OA AND PERFORMANCE RESULTS (FOR W/B= 0.40 AND CURING PERIOD=90 DAYS)

Exp. No.	Levels of parameters Byproduct used as a binder [A]	Byproduct used as FA [B]	Type of byproduct used as a binder [C]	Type of byproduct used as FA [D]	CS (MPa)	STS (MPa)
1	10%	20%	FA	EAFS	72.05	4.58
2	10%	30%	LFS	Iron Slag	64.35	4.07
3	10%	40%	CS	GP	51.18	3.57
4	25%	20%	LFS	GP	44.55	3.46
5	25%	30%	CS	EAFS	46.20	3.87
6	25%	40%	FA	Iron Slag	66.33	4
7	40%	20%	CS	Iron Slag	36.22	3.15
8	40%	30%	FA	GP	64.9	3.8
9	40%	40%	LFS	EAFS	39.38	2.76

The deviation sequence $\Delta_{0i}(k)$ is calculated using (2):

$$\Delta_{0i}(k) = |x_0^*(k) - x_i^*(k)| \quad (2)$$

where $x_0^*(k)$ is the reference sequence and $x_i^*(k)$ is the comparability sequence. The results of all Δ_{0i} for i = 1 to 9 are presented in Table XX.

TABLE XIX
THE SEQUENCE OF EACH PERFORMANCE CHARACTERISTIC AFTER DATA PROCESSING

Reference sequence / Exp. No.	CS	STS
	1.0000	1.0000
1	1.0000	1.0000
2	0.7851	0.7198
3	0.4175	0.4451
4	0.2325	0.3846
5	0.2785	0.6099
6	0.8404	0.6813
7	0.0000	0.2143
8	0.8004	0.5714
9	0.0882	0.0000

TABLE XX
THE DEVIATION SEQUENCES

Comparability sequence	Deviation sequence	
	CS	SPT
Exp. No.	1.0000	1.0000
1	0.0000	0.0000
2	0.2149	0.2802
3	0.5825	0.5549
4	0.7675	0.6154
5	0.7215	0.3901
6	0.1596	0.3187
7	1.0000	0.7857
8	0.1996	0.4286
9	0.9118	1.0000

B. Calculating the Grey Relational Coefficient and the Grey Relational Grade

The grey relational coefficient for each of the experiment of the L_9 OA can be calculated using (3):

$$\zeta_i(k) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{0i}(k) + \zeta\Delta_{max}} \tag{3}$$

where $\Delta_{0i}(k)$ is the deviation sequence among reference sequence $x_0^*(k)$ and comparability sequence $x_i^*(k)$, and ζ is the distinguishing or identification coefficient and its value is taken as 0.5. The grey relational coefficient is presented in Table XXI.

TABLE XXI
GREY RELATIONAL GRADE AND ITS RANK IN THE OPTIMIZATION PROCESS

Exp. no.	Grey relational coefficient		Grey relational grade $\Upsilon_i=½(\zeta_i(1)+\zeta_i(2))$	Rank
	CS $\zeta_i(1)$	SPT $\zeta_i(2)$		
1	1.0000	1.0000	1.0000	1
2	0.6994	0.6408	0.6701	3
3	0.4619	0.4740	0.4679	6
4	0.3945	0.4483	0.4214	7
5	0.4093	0.5617	0.4855	5
6	0.7580	0.6107	0.6844	2
7	0.3333	0.3889	0.3611	8
8	0.7147	0.5385	0.6266	4
9	0.3542	0.3333	0.3437	9

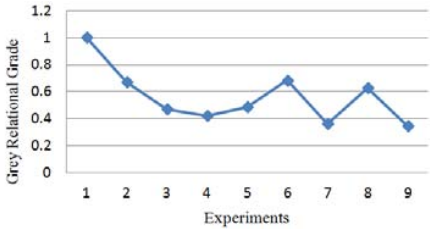

Fig. 2 Grey relational grade

The Grey relational grade is now computed by averaging the Grey relational coefficients corresponding to each performance characteristic and is given by (4):

$$\Upsilon_i = \sum_{k=1}^{n} \zeta_i(k) \tag{4}$$

where Υ_i is the Grey relational grade for the i_{th} experiment and n is the number of performance characteristics. Table XXI and Fig. 2 show the grey relational grade for each of the experiment conducted as per L_9 OA. The higher grey relational grade indicates that the corresponding experimental result is closer to the ideally normalized value. As observed from Table XXI it can be said that experiment 1 has the best multiple performance characteristics among nine experiments as it has the highest Grey relational grade. Thus, it can be seen that in the present study, the optimization of the complicated multiple performance characteristics of concrete has been converted into the optimization of one grey relational grade only.

Due to the orthogonality of experimental design, it is possible to separate out the effect of each parameter on the grey relational grade at different levels. The mean of the grey relational grade for each level of the parameters is summarized and shown in Table XXII. The total mean of the Grey relational grade for all the nine experiments is calculated as 0.5623.

TABLE XXII
RESPONSE TABLE FOR THE GREY RELATIONAL GRADE

Symbol	Parameter	Grey relational grade			Main effect (max-min)	Rank
		Level 1	Level 2	Level 3		
A	Byproduct used as a binder (%)	0.7127	0.5304	0.4438	0.2689	2
B	Byproduct used as FA (%)	0.5942	0.5941	0.4987	0.0955	4
C	Type of byproduct used as a binder	0.7703	0.4784	0.4382	0.3321	1
D	Type of byproduct used as FA	0.6098	0.5719	0.5053	0.1045	3

Total mean value of the Grey relational grade =0.5623
Optimal Parameters = A1 B2 C1 D1

Fig. 3 shows the Grey relational grade obtained for different process parameters. The mean of the Grey relational grade for each parameter is shown by the horizontal line. Basically, the larger the value of Grey relational grade, the closer will be the product quality to the ideal value. Thus, a larger Grey relational grade is desired for optimum performance. Therefore, the optimal parameter setting for better compressive and split tensile strength is A1 B2 C1 D1 as shown in Table XXII. So the optimal parameters are quantity of byproduct used as binder (%) at level 1, quantity of byproduct used as fine aggregate (%) at level 2, type of byproduct used as binder at level 1and type of byproduct used as fine aggregate at level 1. Thus, it can be concluded that most optimum results can be obtained with 10% replacement of cement by FA along with 30% replacement of fine aggregates by EAFS. This optimal level of the process parameters is the level with the highest Grey relational grade. Furthermore, ANOVA has also been performed on Grey relational grade to obtain contribution of each process parameter affecting the two process characteristics, i.e. CS and STS jointly and is discussed in the following section.

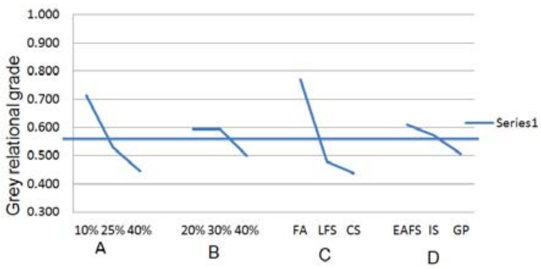

Fig. 3 Effect of parameters on the multi-performance characteristics

C. Analysis of Variance (ANOVA)

The purpose of ANOVA is to investigate which parameter significantly affects the strength performance characteristics of the resulting concrete. ANOVA for Grey relational grade is presented in Table XXIII. The percentage contributions for each term affecting Grey relational grade are shown in Fig. 4. The figure clearly shows that type of byproduct used as a binder is the dominant parameter which contributes in improving the CS as well as STS at 90 days curing period.

The results of GRA for all other combinations of water to binder ratios and curing periods were performed in a similar manner as above. The summary of the GRA is given in Table XXIV.

TABLE XXIII
ANOVA OF GREY RELATIONAL GRADE

Parameter	Degrees of freedom	Sum of squares	Mean squares	F ratio	Percentage contribution (ρ)
Byproduct Used as Binder (%) [A]	2	0.1130	0.0565	6.74	32.74
Byproduct Used as FA (%) [B]	2	0.0182	0.0091	1.09	5.28
Type of Byproduct used as Binder [C]	2	0.1971	0.0986	11.75	57.12
Type of Byproduct used as FA [D]	2	0.0168	0.0084		4.86
TOTAL	8	0.3451	0.1726		100.00

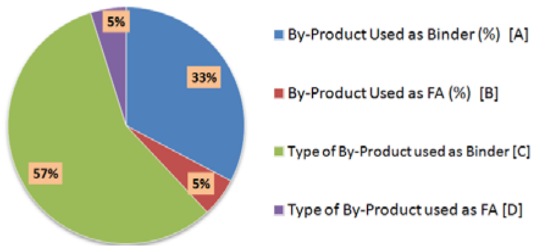

Fig. 4 Percentage contributions of factors on the Grey relational grade

VI. Results and Discussion

In this study, the best possible levels of partial replacement of binder and fine aggregates in the mix proportions were investigated for maximization of CS and STS using the Taguchi based GRA method. The performance statistics for "the larger the better" situations are evaluated for maximization of the strength properties of concrete. For detailed calculations, the response data for one set of w/b ratio and curing period (w/b=0.40 and curing period=90 days), as given in Table XXII, were analyzed using ANOVA at a 0.05 level of significance, to examine the variation in the measured properties of the concrete. Mix proportions in Table XVIII were selected as factors, whereas hardened properties of the concrete mixtures were the dependent variables. GRA is performed to determine the statistically significant factors, and the data analysis is presented in Table XXII. This analysis finally gives the percentage contribution of each control factor so as to determine the level of its statistical importance or significance in the model as shown in Table XXIII. The percentage contribution gives an idea about the degree of contribution of the factors to the measured/output response. If the percentage contribution of the factor is high, than the contribution of the factor for that particular response is more and vice versa. The summary of the GRA for all the combinations of w/b ratios of 0.48, 0.44 and 0.40 and curing periods of 7, 28 and 90 days were performed in a similar manner, and the summary of the analysis is presented in Table XXIV.

A. Effect of Curing Age on Optimal Mix Design Parameters

1. At 7 Days of Curing Period (i.e. at an Early Age)

Table XXIV provides the summary of the Grey-Taguchi analysis for finding the optimal mix design parameters. The table also elucidates the optimal percentage replacement and the percentage contribution of each parameter towards the CS of resulting concrete. It is observed from the first three rows of the table that at 7 days curing, for all water-binder ratios, replacement of cement by FA gives the optimal result, whereas IS replacement for sand provides the optimal strength results only for higher w/b ratios of 0.44 & 0.48. However, at a lower w/b ratio of 0.40, EAFS as a replacement for sand provides better results. Also, it is observed that for all w/c ratios, 10% is the optimum %age of FA replacement contributing to higher strength at early ages, whereas 40% of sand replacement by IS at w/b ratios of 0.48 & 0.44

contributes positively to strength gain at an early age. For lower w/c ratios, 20% of sand replacement by EAFS provides the optimal strength results. Thus, it can be concluded that at early ages, the replacement material and its percentage replacement of cement remain constant at all w/b ratios, whereas, on the other hand, for the replacement of sand, the type of material and its percentage replacement remains constant i.e. 40% IS at higher w/b ratios and it changes to 20% EAFS only at lower w/b ratios.

TABLE XXIV
SUMMARY OF GREY-TAGUCHI ANALYSIS FOR OPTIMAL PARAMETERS

Exp. No.	Curing period (Days)	w/b ratio	Optimal parameters	Optimal parameters				Rank				% Contribution			
				A	B	C	D	A	B	C	D	A	B	C	D
1	7	0.48	A1B3C1D2	10	40	FA	IS	1	4	2	3	72.13	1.06	21.15	5.3
2	7	0.44	A1B3C1D2	10	40	FA	IS	1	4	2	3	56.45	2.19	31.21	10.16
3	7	0.4	A1B1C1D1	10	20	FA	EAFS	1	4	2	3	48.72	1.65	29.32	20.3
4	28	0.48	A1B2C1D1	10	30	FA	EAFS	1	4	2	3	77.14	1.64	16.5	4.73
5	28	0.44	A1B2C1D1	10	30	FA	EAFS	1	4	2	3	53.01	1.01	41.15	4.83
6	28	0.4	A1B2C1D1	10	30	FA	EAFS	2	3	1	4	26.82	10.72	61.99	0.47
7	90	0.48	A1B2C1D2	10	30	FA	IS	2	4	1	3	45.7	0.4	49.1	4.8
8	90	0.44	A1B2C1D1	10	30	FA	EAFS	2	4	1	3	28.9	2.32	65.43	3.35
9	90	0.4	A1B2C1D1	10	30	FA	EAFS	2	4	1	3	32.74	5.28	57.12	4.86

2. At 28 Days Curing Period (i.e. at Normal Age)

On observing the tabulated analysis results at 28 days curing, for all water-binder ratios, we see that the replacement of cement by FA gives the optimal result than other materials, whereas, on the other hand, replacement of sand by EAFS gives the optimal result than other materials. Also, it is observed that for all w/b ratios, 10% is the optimum percentage of FA replacement contributing to higher strength at a normal age, whereas 30% of sand replacement by EAFS provides the optimal strength results. Thus, it can be concluded that at a normal age, curing of 28 days, the replacement material and its percentage replacement values for both cement and sand remain constant for all w/b ratios.

3. At 90 Days of Curing Age

On analyzing the results at 90 days curing, for all water-binder ratios, it is found that replacement of cement by FA gives the optimal result, whereas, IS replacement for sand provides the optimal strength results only for higher w/b ratio of 0.48. However, at lower w/b ratios of 0.44 & 0.40, EAFS as a replacement for sand provides better results. Also, it is observed that for all w/b ratios, 10% is the optimum percentage of FA replacing cement contributing to higher strength, whereas 30% of sand replacement by IS at w/c ratios of 0.48 contributes positively to strength gain. For lower w/b ratios, 30% of sand replacement by EAFS provides the optimal strength results. Thus, it can be concluded that at 90 days, the replacement material and its percentage replacement for cement remains constant at all w/b ratios; on the other hand, for the replacement of sand, the type of material and its percentage replacement remains constant (i.e. 30% IS) at higher w/b ratio of 0.48. However, it changes to 30% EAFS only at lower w/b ratio of 0.40 and 0.44.

B. Percentage Contribution towards the Strength of Various Optimal Parameters at Different Curing Periods

The results indicating the percentage contribution of optimal parameters towards concrete strength are also tabulated in Table XXIV. The effect at different curing ages is presented below:

1. At 7 Days Curing Period (i.e. at an Early Age)

At 7 days of curing, for all w/b ratios, 10% of byproduct to be used as partial replacement of cement is the optimal parameter which contributes maximum towards the strength of the resulting concrete. It is observed that its contribution is maximum at higher w/b ratio of 0.48, i.e.72.13% and it decreases to 48.72% as the w/b is decreased to 0.40, whereas, at lower w/b ratios, the contribution of type of cement replacement material towards concrete strength, (i.e. FA) starts increasing, which is 29.32% at w/b ratio of 0.40. The percentage of sand replacement, as can be seen from Table XXIV, contributes very little and almost remains constant at all the w/b ratios, whereas the type of replacement as sand does play a slightly better role only for lower w/b ratios.

2. At 28 Days of Curing Period

At 28 days of curing, for higher w/b ratios, the percentage of cement replacement material contributes the most towards the concrete strength, whereas at lower w/b ratios, the type of cement replacement material contributes maximum towards the strength of resulting concrete. As can be observed from Table XXIV, the percentage contribution towards the strength of 10% replacement of cement is maximum at 77.14% at w/b ratio of 0.48 whereas, its value is 26.82% at w/b ratio of 0.40. The percentage contribution of FA towards strength gain is 16.50% at w/b ratio of 0.48; whereas, it is 61.99% at lower at w/b ratio of 0.40. The percentage contribution of the parameters, namely the type of sand replacement and its percentage replacement contributes very little at all the w/b ratios.

3. At 90 Days of Curing Period

At 90 days of curing, for all w/b ratios, the type of byproduct used as cement replacement material, which is FA, among the three materials, contributes the maximum to the strength of resulting concrete and its contribution is maximum at 65.43% at w/b ratio of 0.44. However, for higher w/b ratio of 0.48 both the percentage and types of cement replacement material contribute almost equally to concrete strength. The percentage of cement replacement contributes maximum to the strength i.e. 45.7% at higher w/b ratio of 0.48, and its contribution decreases to 32.74% at lower w/b ratio of 0.40. The type of sand replacement and its percentage replacement contributes very little towards the strength of such concrete at all the w/b ratios.

C. Confirmation Experiment to Verify Optimum Mix-Design Proportions

Optimum mix-design proportion obtained using the Taguchi method was verified by conducting an experiment to check whether CS and STS can really be maximized by the proposed optimum mix design proportions. Same materials and the same conditions were used in the experiment in order to compare the results. 12 150 mm cube samples and 150x300 mm size cylinders were cast according to the optimum mix proportion obtained from the Taguchi method. These samples were tested for CS and STS at 28 days by using the related standard. The results are tabulated in Table XXV, and it is observed that the mixture resulted in more CS mixes. The verification study results showed that proposed optimum mix proportions satisfy the expected maximization for CS and STS.

The optimum combination of control factors for confirmation experiment at 28 days of curing period and for all the w/b ratios is as given below.

- Percentage of byproduct to be used as partial replacement of cement-- 10%
- Percentage of byproduct to be used as partial replacement of fine aggregate--30%
- Type of replacement as binder--- FA
- Type of replacement as Fine aggregate--- EAFS

TABLE XXV
RESULTS OF EXPERIMENTAL WORK ON THE OPTIMUM MIX-DESIGN PROPORTIONS AT 28 DAYS OF CURING AGE

Exp. No.	w/b ratio	Optimal Parameters	Control Mix Results		Experimental Results	
			CS	STS	CS	STS
1	0.48	A1B2C1D1	42.06	3.45	47.15	3.46
2	0.44	A1B2C1D1	45.13	3.82	48.79	3.87
3	0.4	A1B2C1D1	51.05	4.47	54.15	4.48

VII. SUMMARY AND CONCLUSIONS

The optimization of process parameters for optimum mix design was performed using Taguchi's experimental design method. An L_9 OA was used for four control factors, each with three levels for the experimental plan. The selected process parameters for analysis along with their levels were: percentage of byproduct to be used as partial replacement of Cement (10, 25, 40%); percentage of byproduct to be used as partial replacement of fine aggregate (20, 30, 40%); type of cement replacement material (FA, LFS, CS); and type of sand replacement material (EAFS, IS, GP). Based upon the conducted study, it can be concluded that among the four selected process parameters, the percentage of byproduct to be used as partial replacement for cement significantly affects the quality characteristic, i.e., CS and STS at all the w/b ratios and at 7 and 28 days of curing. However, at later ages, the type of replacement as a binder has a more significant effect on the quality characteristic, i.e., CS and STS at all the w/b ratios. Also, FA as a binder material significantly contributes to strength at all w/b ratios; however, the highest contribution is obtained at a w/b ratio of 0.48 and at curing period of 28 days. The major conclusion can be summarized as follows:

1. FA replacement at 10% level of the binder content is the most optimum parameter which positively affects the strength characteristics of concrete at all w/b ratios and at all curing ages.
2. The optimal parameter for the replacement of cement at 7 and 28 days of curing period is the percentage of byproduct as partial replacement i.e. 10%, which contributes maximum to the compressive as well as split tensile strength.
3. The optimal parameter for the replacement of fine aggregate is IS at 7 days of curing, but as curing period increases to 90 days, EAFS contributes more to the strength characteristics in comparison to other parameters.
4. The optimum percentage of the replacement for fine aggregate is 40% at 7 days curing, but it reduces to 30% at 28 and 90 days of curing.
5. As water to binder ratio decreases from 0.48 to 0.40, the optimal byproduct used as a replacement of fine aggregate changes from IS to EAFS.
6. The major contributor towards strength gain is the type of byproduct used as a replacement for cement and not the type of byproduct used as a replacement of fine aggregate.
7. The study shows that the Taguchi method can be used efficiently and economically for designing the experiments and for determining the optimum process parameters.

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