Optimization of Self-Compacting Concrete Using Taguchi Based Grey-Relational Analysis Method

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Abstract- *Self-compacting concrete (SCC) is a special concrete that does not require vibration for placing and compaction. Assessment of the optimal SCC concrete mixture is an important issue to obtain desired quality. In this study optimization of SCC mix is done using Weighted-Grey Taguchi method. This study integrates Grey Relational analysis and Analytical Hierarchy process for assigning weights to different results or responses into the Taguchi method to propose Weighted Grey-Taguchi method. This method can be employed to assess the optimal mixture with multiple results. In this study the optimization of SCC concrete is done using the results obtained from previous research investigation in which the concrete mixture is obtained by partial replacement of cement using bottom ash and fly ash and by adding super plasticizer for increasing the flow of the concrete. The seven responses or results considered are Slump flow, T50, Compressive strength, Acid attack, Sorptivity, Sulphate attack, Water absorption. Optimization is done by varying the variables like Bottom ash by 5,10 and 15 (% by weight of cement), Fly ash by 25,30 and 35 (% by weight of cement) and Super plasticizer by 0.5,0.6 and 0.7 (% by weight of cement).Taguchi grey relational analysis method of optimization is used as it also provides the information about the main effect factor or material which influence the results of concrete mix.*

Keywords- Granite Powder, River Sand, M-Sand, Concrete, Percentages, self compacting concrete, Replacement.

I. INTRODUCTION

For several years, the problem of the durability of concrete structures has been a major problem posed to engineers. To make durable concrete structures, sufficient compaction is required. Compaction for conventional concrete is done by vibrating. Over vibration can easily cause segregation.

In conventional concrete, it is difficult to ensure uniform material quality and good density in heavily reinforced locations. If steel is not properly surrounded by concrete it leads to durability problems. The answer to the problem may be a type of concrete which can get compacted into every corner of form work and gap.

II. OPTIMIZATION

The tools and techniques used in optimization have been proven successful in meeting the challenge of continuous improvement in many manufacturing organizations. “Optimization is the act of obtaining the best result under given circumstances”. Optimization can be defined as the process of finding the conditions that give the maximum or minimum of a functions i.e., given that input parameters, what combination of those input parameters would give us the best results.

To determine the controllable factors that will affect the desired response. To minimize the effect of uncontrollable factors or noise factors. To determine the optimum combination of controllable factors that will give the best value of the desired response. Multi-response optimization where a balance is to be achieved between a numbers of desired responses.

TAGUCHI METHOD OF OPTIMIZATION

The assessment of an optimal mixture for obtaining desired quality is an important issue in the field of engineering. The problem of optimal mixture assessment can be described as y=f(x1,x2,....,xn),in which y denotes the key response used to represent quality and x1 to xn are the control factors that will mainly affect the performance of the response. If each control factor has three input levels,3n mixtures (factor level combinations) are required for a full factorial design to determine the optimal mixture by the traditional design of experiment(DOE).

However, two problems, namely large time/cost requirements for experiments and complex calculation resulting from full factorial design and fractional factorial design, respectively will be encountered in practice. Therefore, a Taguchi method employing an orthogonal array and signal –to-noise ratio (s/n ratio) analysis was proposed to improve the effectiveness and efficiency of DOE by reducing the time/cost of experiments.

Both conventional DOE method of concrete mix design and Taguchi methods can only consider a single response at a time. But, in practice, the presentation of quality ought to be considered in various responses, i.e.., the problem of optimal mixture assessment ought to be described as (y1,y2...ym)=f(x1,x2....xn)where y1 to ym are different responses used to represent quality. To solve the optimal mixture problems with multiple mixtures is determined by engineering experience of the calculations and the possibility of erroneous judgments.

Therefore, a Grey-Taguchi method employing grey relational analysis in the Taguchi method has been proposed to effectively solve the optimal mixture problem with multiple responses.

III. GREY RELATIONAL ANALYSIS

Grey Relational Analysis (GRA) is an important part of grey system theory pioneered by Professor Deng in 1982. A grey system means that a system in which part of information is known and part of information is unknown. With this definition, information quantity and quality form a continuum from a total lack of information to complete information.
Generally the single response optimization is a common method to solve the optimization problems. There are many methods available for the multi response optimization and Grey Relational Analysis (GRA) is one of them. Here, the GRA is introduced to convert the multi response system into single response and also to find out the optimal mix to achieve the good characteristics of self compacting concrete.

The GRA is a method of measurement to determine the degree of approximation among the sequences with the help of Grey Relational Grade (GRG).So, in this study, the GRG has been introduced to determine the optimal combination from the varying factors of bottom ash, fly ash and super plasticizer up to three levels.

Selection of control factors and their levels are done on the basis of some preliminary trial experiments and with reference to many literature review done on the work. Out of all the constituents such as Cement (OPC 53), coarse aggregate, fine aggregate, potable water, bottom ash, fly ash, Super plasticizers; three were chosen as control factors because they affect the performance of SCC. The control factors are bottom ash, super plasticizer, fly ash. The levels are fixed as “THREE” since the effect of these factors affecting the compressive strength varies nonlinearly and shown in table-1.

TABLE – 1 VARIABLES AND LEVELS

VARIABES	LEVELS		
Bottom ash	5	10	15
Fly ash	25	30	35
Superplasticizer	0.5	0.6	0.7

To study the effect of control factors an orthogonal array L9 is developed based on the no. of factors and no. of levels. They are arranged such that the columns for independent variables are orthogonal to each other.

Generally, L9 orthogonal array has 9 rows and 3 columns. Each column represents a factor and each row represents a specific mix condition which may provide an optimum mix. Here 33 is used in which the base 3 indicates the presence of three levels and the power 3 indicates three factors which provide us the desired output taken from the published results is shown in Table-2.

DATA ON FRESH AND HARDENED CONCRETE PROPERTIES FROM PUBLISHED PAPER USED FOR ANALYSIS

Performance of self compacting concrete with varying combinations of bottom ash, fly ash and super plasticizer in fresh and hardened state is presented in table -3 are taken for discussion.

TABLE-2 L9 ORTHOGONAL ARRAY

Experiment No	Factor A	Factor B	Factor C
1.	1	1	1
2.	1	2	2
3.	1	3	3
4.	2	1	2
5.	2	2	3
6.	2	3	1
7.	3	1	3
8.	3	2	2
9.	3	3	1

Table-3- DATA ON FRESH AND HARDENED CONCRETE PROPERTIES FROM PUBLISHED PAPER USED FOR ANALYSIS

Mix ID	Slump flow (cm)	T50 Slump (sec)	Compressive Strength (N/mm^2)
X1	61	4.53	41.3
X2	64.5	3.91	40.2
X3	67	3.4	39
X4	65	3.46	42.3
X5	67	3.44	40.
X6	63	4.23	38.6
X7	69	3.23	38.9
X8	62.5	4.47	37.1
X9	66	3.67	35.5

DATA ON DURABILITY PROPERTIES

The durability results for various combinations of bottom ash, fly ash and super plasticizer are presented in the table-4.

IV. METHODOLOGY

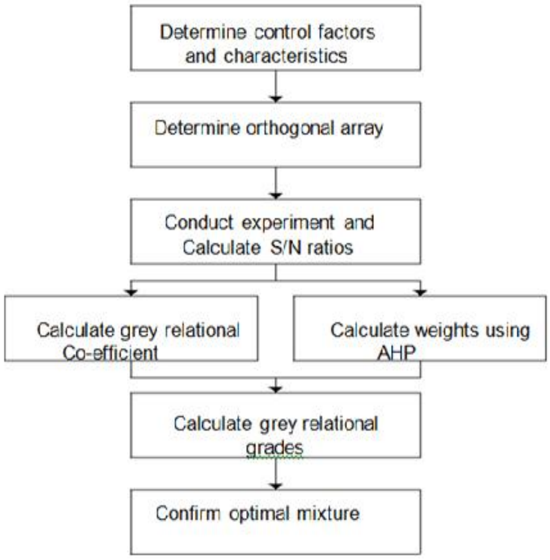

Table-4- DATA ON FRESH AND HARDENED CONCRETE PROPERTIES FROM PUBLISHED PAPER USED FOR ANALYSIS

Mix ID	Water Absorption % of voids	Sorptivity $mm/sec^{1/2}$	Acid attack (Loss in compressive strength) 28 days %	Acid attack 56 days %	Sulphate attack (Loss in compressive strength) 28 days %	Sulphate attack 56 days %
X1	1.612	0.0408	4.600	6.053	5.085	6.053
X2	2.549	0.00541	4.229	7.214	1.493	2.985
X3	1.756	0.00375	5.897	8.462	4.359	4.615
X4	2.050	0.00458	3.310	4.492	1.891	2.128
X5	2.746	0.01540	3.951	5.926	4.938	5.679
X6	2.992	0.02248	6.218	9.585	6.477	8.808
X7	2.921	0.01748	2.828	4.370	6.684	9.512
X8	2.380	0.00999	3.235	4.852	5.930	7.547
X9	2.934	0.01290	7.324	10.986	7.042	10.141

ORTHOGONAL ARRAY AND S/N RATIO

Orthogonal arrays and S/N ratios are two main components of the Taguchi method.An orthogonal array is used to reduce testing time/ cost. If an experiment has 3 control factors with three levels, all possible $n = 3^3$ mixtures are required to test for assessing the optimal mixture by using a full factorial design of experiment. By using the orthogonal array $L_9 3^3$, only 9 mixtures are required to estimate the optimal mixture.

To drastically reduce the number of tests while still gaining significant insight on important factors and optimal settings, Taguchi recommended the use of eighteen basic orthogonal fractional factorial arrays known as the standard orthogonal array.

On the analysis side, Taguchi advocated the S/N ratio as a single indicator that jointly and simultaneously considers the average value and standard deviation of test results to determine the relative importance of the factors under study. The S/N ratio can be categorized into three types as follows. Selection of the appropriate S/N ratio depends on the features of responses.

1. The smaller-the-better (s) type

$$SN_s = -10\log\left(\sum_j \frac{y_j^2}{n}\right) \quad (1)$$

2. The larger-the-better (L) type

$$SN_L = -10\log\left(\sum_j \left(\frac{1}{y_j^2}\right) \Big/ n\right) \quad (2)$$

3. The nominal-the-better (N) type

$$S/N_{(N)} = 10\log\left(\frac{\mu^2}{\sigma^2}\right) \quad (3)$$

In the above formula y(i) represents the responses or results obtained from SCC concrete mix testing, σ represent variance of the test results and μ represents mean value of the results and n is the number of results from 3 cubes.

GREY RELATIONAL ANALYSIS

STEP 1: PRE-PROCESSING OF RAW DATA

Grey relational analysis can be used to consider multiple responses at the same time and then to provide a comprehensive index to represent the evaluation of responses. Grey relational analysis has been widely employed in various fields and has thus demonstrated its applicability.

Pre-processing of the raw data matrix is required to satisfy the comparability (non-dimension, scaling, and polarization) among responses before conducting grey relational analysis.

STEP 2: GREY RELATION CO-EFFICIENT

Then the grey relational co-efficient εi(k) is assigned to explain the relation between desirable and the experimental normalized data. The grey relational co-efficient can be calculated using the following equation,the raw data matrix,D

$$D = \begin{matrix} Xo(1) & Xo(2) & \ldots\ldots\ldots\ldots & Xo(m) \\ X1(1) & X1(2) & \ldots\ldots\ldots\ldots & X1(m) \\ X2(1) & X2(2) & \ldots\ldots\ldots\ldots & X2(m) \\ \ldots\ldots & \ldots\ldots & \ldots\ldots\ldots\ldots & \ldots\ldots \\ Xn(1) & Xn(2) & \ldots\ldots\ldots\ldots & Xn(m) \end{matrix}$$

in which X0 is the reference set, and x1 to xn are the comparison set. Each set is composed of m responses, and xi(j) represents the evaluation of the ith series on the jth response. The reference series can be composed of measured data or assumed data based on the requirements of evaluation. The raw data matrix can be pre-processed (the smaller-the- better type) or (the larger-the-better type) depending on the feature of response.

$$ri(j) = \frac{xi(j)}{OB} + 2 \;\ldots\ldots(4) \qquad ri(j) = \frac{xi(j)}{OB} \;\ldots\ldots\ldots(5)$$

OB indicates the object value of responses. In the smaller-the-better type of response, such as cost, OB can be defined as the minimum value of the response. In the larger-the-better type of response, such as benefit, OB can be defined as the maximum value of the response. ro(j) and ri(j) are the pre-processed values of xo(j) and xi(j), respectively. The difference between ro(j) and ri(j) can be calculated as

D0i(j) = |r0(j) _ ri(j)| and then the difference matrix, D, is constructed as follows.

$$\Delta = \begin{matrix} \Delta_{01}(1) & \Delta_{01}(2) & ---- & \Delta_{01}(m) \\ \Delta_{02}(1) & \Delta_{02}(2) & ---- & \Delta_{02}(m) \\ \Delta_{03}(1) & \Delta_{03}(2) & ---- & \Delta_{03}(m) \\ \ldots\ldots & \ldots\ldots & \ldots & \ldots\ldots \\ \Delta_{0n}(1) & \Delta_{0n}(2) & ---- & \Delta_{0n}(m) \end{matrix}$$

The grey relational coefficient, Є0i(j), between ro(j) and ri(j) is defined

As

$$\in 0i(j) = \frac{\Delta\min + \rho\Delta max}{\Delta oi(j) + \rho\Delta max} \;\ldots\ldots\ldots\ldots(6)$$

STEP 3: GREY RELATIONAL GRADE

Grey Relational Grade (GRG) is a weighted sum of the grey relational co-efficient.

STEP 4: Rank the preference order. The largest GRG gives us the optimum combination of mix.

OPTIMIZATION USING WEIGHTED GREY-RELATIONAL ANALYSIS (GRA) QUALITY CHARACTERISTICS

The first step in the GRA is finding S/N ratio of experimental result with respect to the quality characteristics, this S/N ratio can be divided into three criteria in optimization in GRA, which are commonly known as “larger the better”, “smaller the better” and “nominal the better” shown in table-5

Optimization using GRA

For calculation purpose results tabulated in table 3 and 4 are used.

STEP 1: CALCULATING SIGNAL TO NOISE RATIO(S/N OR SN RATIO)

The signal to noise ratio for the seven response values are calculated and tabulated below in table

Table-5 Quality Characteristics

S.No	Response	Response ID	Quality Characteristics
1	Slump flow	R1	Larger is Better
2	T50 Slump	R2	Smaller is Better
3	Compressive Strength	R3	Larger is Better
4	Water Absorption	R4	Smaller is Better
5	Sorptivity	R5	Smaller is Better
6	Acid attack	R6	Smaller is Better
7	Sulphate attack	R7	Smaller is Better

Table-6 S/N Ratio Values for 9 Results

Mix ID	*Compressive Strength N/mm2*	*Acid attack %*	*Sulphate attack %*	*Sorptivity* Mm/sec1/2	*Water Absorption %*	*Slump flow* mm	*T50* sec
X1	32.319	-15.639	-15.639	47.958	-4.147	55.706	-13.122
X2	32.084	-17.163	-9.498	46.020	-7.815	56.191	-11.843
X3	31.821	-18.549	-13.283	47.958	-4.929	56.521	-10.629
X4	32.526	-13.048	-6.559	46.020	-6.235	56.258	-10.781
X5	32.149	-15.455	-5.085	36.478	-8.774	56.521	-10.731
X6	31.731	-19.631	-18.897	33.151	-9.519	55.986	--12.52
X7	31.798	-12.809	-19.565	35.391	-9.310	56.776	-10.182
X8	31.387	-13.718	-17.555	40.000	-7.532	55.917	-13.0062
X9	31.00457	-20.8168	-20.1216	37.7211	-9.3492	56.3908	-11.2933

Table-7 GREY RELATIONAL CO-EFFICIENT VALUE

Mix ID	Compressive Strength N/mm2	Acid attack %	Sulphate attack %	Sorptivity mm/sec1/2	Water Absorption %	Slump flow mm	T50 Sec
X1	0.986	0.551	0.597	1	0.436	0.981	1
X2	0.95	0.656	0.294	0.956	0.821	0.99	0.903
X3	0.922	0.770	0.455	1	0.518	0.996	0.810
X4	1	0.408	0.211	0.959	0.655	0.991	0.822
X5	0.957	0.539	0.567	0.760	0.922	0.996	0.817
X6	0.913	0.873	0.869	0.691	1	0.986	0.954
X7	0.92	0.397	0.938	0.737	0.978	1	0.776
X8	0.877	0.442	0.744	0.834	0.791	0.985	0.992
X9	0.839	1	1	0.786	0.982	0.993	0.860

CALCULATING WEIGHTS FOR VARIOUS RESPONSES USING AHP PROCESS ANALYTICAL HIERARCHY PROCESS

Analytical Hierarchy Process is the most widely used technique in the decision making process. It was originally developed by Prof. Thomas L. Saaty in 1980. The AHP considers a set of evaluation criteria, and a set of alternative options among which the best decision is to be made. It is important to note that, since some of the criteria could be contrasting, it is not true in general that the best option is the one which optimizes each single criterion, rather than the one which achieves the most suitable trade-off among the different criteria. The AHP generates a weight for each evaluation criterion according to the decision makers " pair-wise comparisons" of the criteria. The higher the weight, the more important is the corresponding criterion. Next, for a fixed criterion, the AHP assigns a score to each option according to the decision makers pair-wise comparisons of the options based on that criterion. The higher the score, the better is the performance of the option with respect to the considered criterion. Finally, the AHP combines the criteria weights and the options scores, thus determining a global score for each option, and a consequent ranking. The global score for a given option is a weighted sum of the scores it obtained with respect to all the criteria.

AHP is a very flexible and powerful tool. It helps us to set priorities and make the best decision when both tangible and non-tangible aspects of decision need to be considered. It not only helps the decision makers to arrive at the best decision, but also provides a clear rationale that it is the best. This is because it reduces the decisions of complex nature to a series of one-one comparisons and then the results are synthesized. Hence AHP is a tool that is able to translate both the qualitative and quantitative evaluations into a multi-criteria ranking and is regarded as the most widely used on.

In this study AHP process is used for assigning weights to each responses or results from the concrete mix testing.

The AHP can be implemented by:

1) Computing the vector of criteria weights,

- Define the objectives
- Select the alternatives
- Arrange in hierarchical structure the objectives, criteria and alternatives

Step 1: Computing the vector of criteria weights
Generating a pair-wise comparison matrix A is the first step in this process. This is done to find the relative importance of different criteria/sub-criteria with respect to the objective. The matrix A shown is an m×m real matrix, where m is the number of evaluation criteria considered. . Each entry $ajk$of the matrix A represents the importance of the jth criterion relative to the kth criterion. If $ajk>$ 1, then the jth criterion is more important than the kth criterion, while if $ajk<$ 1, then the jth criterion is less important than the kth criterion. If two criteria have the same importance, then the entry ajk is 1. The relative importance between two criteria is measured according to a numerical scale from 1 to 9, as shown in Table-8. Hence, the A matrix is formed using this fundamental scale of AHP.

Step 2 : Assigning weights for sub-criteria

The normalized weights for the sub-criteria are obtained finding the geometric means of each row in A matrix and normalizing them. The geometric mean method is usually used to find the relative normalized weights of the criteria/sub-criteria. It is commonly used because of its simplicity, finding the maximum Eigen value with ease and the reduction in the inconsistency in judgment shown in table-9.

TABLE-8 Nine point scale of pair-wise comparison by Saaty(1980)

Value of ajk	Interpolation
1	J and K are equally important
3	J is slightly more important than K
5	J is more important than K
7	J is strongly more important than K
9	J is absolutely more important than K
2,4,6,8	Intermediate values of relative importance

$$\mathbf{GM_i} = \{ a_{i1} \times a_{i2} \times \ldots\ldots \times a_{ij}\}^{1/n}$$
$$W_i = \mathbf{GM_i} / \textstyle\sum_{j=1}^{j=n} \mathbf{GM_i}$$

TABLE- 9 WEIGHTS COMPUTED BASED ON AHP

Responses	Weightage
Compressive strength	0.233951
Acid attack	0.072394
Sulphate attack	0.050349
Sorptivity	0.018912
Water absorption	0.115623
Slump flow	0.254435
T50	0.254435

STEP-5 Calculating Grey Relational Grade Value Based on Weights from AHP and Grey Relational Co-Efficient shown in table-10.

STEP-6 RANKING OF MIXES

Finally rank of the concrete mix is obtained by multiplying weightages of each outcomes obtained from AHP with grey Relational co-efficient obtained from the Grey Relational analysis. Average of each mixes is calculated and rank is provided as per descending order shown in table-11.

TABLE-10 GREY RELATIONAL GRADE VALUE

Mix ID	Compressive Strength N/mm^2	Acid Attack%	Sulphate attack%	Sorptivity mm/sec$^{1/2}$	Water Absorption %	Slump Flow mm	T50 Sec
X1	0.180	0.029	0.0248	0.0189	0.039	0.085	0.2522
X2	0.144	0.034	0.028	0.0149	0.070	0.0121	0.136
X3	0.110	0.041	0.021	0.0189	0.043	0.172	0.094
X4	0.234	0.024	0.017	0.0149	0.052	0.129	0.098
X5	0.153	0.028	0.024	0.007	0.090	0.172	0.097
X6	0.112	0.051	0.037	0.0063	0.115	0.102	0.181
X7	0.117	0.024	0.043	0.007	0.107	0.255	0.084
X8	0.092	0.025	0.031	0.009	0.066	0.092	0.235
X9	0.077	0.072	0.050	0.008	0.108	0.147	0.113

TABLE-11 RANKING OF MIXES

Mix ID	Average Of Grey Relational Grade	Rank
X1	0.09	2
X2	0.077	8
X3	0.072	9
X4	0.0813	6
X5	0.0817	5
X6	0.0866	3
X7	0.0911	1
X8	0.0796	7
X9	0.0826	4

V. CONCLUSION

The fresh, hardened and durability properties of SCC for incorporating bottom ash has been studied and the results has been optimized using Grey Relational Analysis (GRA). The following conclusions were made,

In this analysis of weighted-grey Taguchi method it is concluded that the mix of A3B1C1 (i.e., 0.7%super plasticizer, 5% bottom ash, 20% fly ash).

From Grey Relational Analysis response it can be conclude that Fly Ash is the most significant factor for fresh, hardened and durability properties.

The proposed statistical approach is simple, useful, and a reliable methodology to optimize parameters efficiently. In fut future, this method can be used to optimize and this method can be extended to study other SCC test in both fresh and hardened state and durability test.

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