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The strength of fly ash concrete of experimental design

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Abstract. Cement concrete has always played an essential role in the general development of the construction industry. Many studies improve the properties and durability of cement concrete by adding chemical additives and mineral additives. One of them, fly ash, is one of the most preferred applied mineral additives. Currently, the demand for fly ash is becoming an urgent problem, as it is also can reduce environmental pollution from by-products of thermal power plants not only in Vietnam but also all around the world. To evaluate the factors affecting compressive strength of concrete, such as fly ash, type of cement used, date and designed concrete grade, we based our study on the design of experiment (DOE). The influencing variables have different levels of investigation, which are based on previous studies. With the useful statistical analysis tools, the number of experiments, and the results of the experimental analysis, we can see the influence of each element and their interaction on the compressive strength of the concrete. On that basis, it is possible to choose the option with reasonably selected ingredients to achieve the expected optimal compressive strength.

1. Introduction

1.1. Overview of fly ash and fly ash concrete in the world

Thermoelectric fly ash was discovered to be active as a pozzolan additive in the early 20th century. It was officially used as an additive in concrete production since the mid-20th century, beginning with the study of fly ash applications in concrete of the University of California, Berkely, the USA in 1937. For more than half a century, the application of fly ash as an additive for concrete production, especially in countries with a large coal power output, increasingly popular and increasing volumes.

The scientific basis of mixing mineral additives into the mixed composition of concrete is based on the following aspects. In the first phase, fly ash (FA) is almost inactive but acts as an inert material filling the mixed voids [1–3]. Over time, the hydration process continues to increase the alkaline environment (the concentration of OH- ions increases), thereby activating the potential hydraulic properties in fly ash to create the pozzolanic reaction. The result of the process of the puzzolanic reaction has transformed the $Ca(OH)_2$ component into stable C-S-H ($C_3S_2H_3$, C_4ASH_{12}, C_4AH_{13}) products, which increase the ability to resist waterproof, corrosion, temperature and adds strength to the concrete. So that many types of cement concrete, when using reasonable fly ash, can improve the mechanical properties better than conventional cement concrete. Due to the pozzolanic reaction, the fly ash particles lose their original spherical shape and are gradually covered with a new product layer and, after six months, no longer determine the actual

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condition [4]. The cement hydration process consists of complex reaction chains, with the addition of fly ash, the more complex the reaction processes. The only activity of fly ash particles affects the hydration of the cement, but not all fly ash particles are involved. The micro-aggregates fill the space between the cement particles, contribute to reducing the voids of the cement stone, while also helping to significantly improve the structure of the transition zone between the cement stone and the aggregate. Besides, the presence of mineral additives in the transition area together with the gradual increase of C-S-H products from the pozzolanic reaction increasing the density of the hydration products, the formation of C-S-H takes place in a narrow environment, solidifies the structure of the concrete, increasing the strength of the concrete. The filling effect of mineral additives is highly dependent on their fineness.

There are many scientific works in the world that have partly demonstrated that the properties of concrete are significantly improved when mineral additives are added.

According to ACI 232R [5], fly ash cement concrete (FC) is understood as Portland cement concrete (PC), which uses fly ash with a specific content to partially binder replace the Portland cement binder. According to Michael [6], in the history of development, fly ash is used in cement concrete with varying levels, depending on the purpose of the use of the goal of projects. Typically, to meet the requirements of structural strength, the fly ash ratio is from 15 % – 30 % of the volume of adhesive, at a higher concentration of 30 % – 50 % used for hydropower and dams to control the temperature in mass concrete structures. In recent years, the concrete with a very high fly ash content of more than 50 % has been developed for structural works requiring high strength. Currently, for high-performance concrete (HPC), the use of fly ash is 10 % – 30 % of the adhesive content. In the cement concrete, the amount of fly ash added is equal or higher than the amount of cementless, because fly ash has a smaller density than cement. The studies of Owen [7] by Jiang and associates [8] produce that with high-quality cement concrete depending on the fly ash quality and the amount of cement to be replaced. The level of loss of fly ash cement concrete is usually smaller, which is very suitable for high-temperature construction conditions in our country [9]. According to Mehta [10], using fly ash in high-quality concrete also has the effect of reducing shrinkage, reducing heat cracking, and increasing water resistance. The authors also have researched on the application of fly ash, clearly seeing the advantages of this mineral additive [11–15]. According to research by Konstantin Sobolev and colleagues [16], has obtained significant results on fly ash mortar and fly ash concrete strength at different age dates with two types of class C and F fly ash. Photo The effect of fly ash type and quantity is specifically assessed in the properties such as time and intensity. In particular, the effect of fly ash is assessed specifically by the strength of the mortar at the age of 1, 7 and 28. It is found that the effect of mineral additives is very clear and brings many benefits. Moreover, the results obtained concrete strength of all types achieved results above the standard of 20 Mps at 7 days of age and best at 365 days up to 47.7 MPa when mixed 15 % simultaneously. In the study of Anjali Yadav and Nikhi Kumar Yadav [17] also about the use of flying in concrete pavement, the amount of fly ash used ranged from 0 % to 60 %. The compressive strength of concrete was determined at 7 and 28 days of age, showing that if the content increases, the strength of the concrete decreases, it is safe to use fly ash up to 40 %, and more the strength of the concrete is not satisfactory. Analysis and design of fly ash concrete used for road foundations, research by A. Hilmi Lav et al [18] with the main reason for this research is to want to reduce costs and use industrial waste. Level F fly ash content is added to make up 2 %, 4 %, 8 % and 10 % by total weight. Test batches were performed to adjust the fly ash appropriately. The mechanical properties are then checked to obtain the basic properties of the cement stabilizer, thereby analyzing the pavement texture. In the study of Jin Huang, Huayou Su [19] used shows that the workability of fly ash concrete can significantly improve, and the compressive strength is similar with ordinary concrete after 28 days. In research of Uma Maguesvari Muthaiyan and Sundararajan Thirumalai [20], showed the result of some main characteristics of fly ash concrete with differential level of class C fly ash ranging from 0 % to 20 %, their suggestion should use minimum cement content 250 kg/m^3 and with 10 and 20 % of replacement of cement by fly ash. Besides, the increasing content of fly ash, the reducing compress strengthen of concrete.

The selection of the appropriate ratio of fly ash in concrete is based on the purpose of the survey to fabricate concrete with a certain replacement flight content while still ensuring the necessary features for the application of the concrete type. This concrete is in construction of high-grade road foundations, pavement for traffic and for prefabricated structures. Therefore, in the research scope of the paper, some concrete grades selected for specific survey are the following: C20, C30, C40. The ratio of fly ash/binder has a great influence on the strength of concrete, depending on the purpose of the strength to be achieved to choose the appropriate ratio. According to the recommendations of ACI 211.4R [21] for concrete with strength greater than 35 MPa, the ratio of 15 % – 25 % (type F) and 20 % – 35 % (type C) should be used. As recommended by EN206 [22] standard, use the ratio from 15 % – 33 % (type F) and 15 % – 35 % (type C). In this paper, the authors' research only compressive the strengthen of fly ash concrete basing on some key factors namely concrete of grade, percentage of fly ash in cementitious, and type of cement by DOE approach.

2. Materials and methods

2.1. Design of experiment

Experimental Design mathematical methodology is a branch of applied statistics, used to plan and conduct experiments as well as to analyze and interpret data which is obtained from experiments. Over the past two decades, the design of experiment (DOE) has expanded across a wide range of industries. It is a handy tool often that is used to improve product quality and reliability [23]. Since the 1920s, Ronald A. Fisher has conducted a study in agriculture to increase productivity growth in England. After giving an experimental design and the official was the first to start using DOE. By 1935, his book about DOE was written for the first time, which explains how valid conclusions can be drawn from experiments with nuisance factors. In which he analyzed the presence of objective factors subject to the fluctuation of weather conditions such as temperature, precipitation. Then, the experimental design process to optimize the process, the Feedback Surface Method (RSM) was also mentioned by George Box, who is also from the UK. In the 1550s, W. Edwards Deming was interested in experimental design as well as statistical methods. Genichi Taguchi is a Japanese statistician interested in quality improvement methods, by introducing the Loss function and extensive experiments with "external arrays" in DOE as an advanced approach in Six SIGMA initiatives [24].

Suppose there are two factors A, B affect the output variable Y, then the relational equation is as follows (equation 1):

$$Y_{\mathrm{ij}k} = \mu + \tau_i + \delta_j + (\tau\delta)_{\mathrm{ij}} + \varepsilon_{\mathrm{ij}k} \tag{1}$$

where:

μ represents the overall mean effect;

τ_i is the effect of the i_{th} level of factor A $(i = 1, 2, \ldots, n_a)$;

δ_j is the effect of the j_{th} level of factor B $(j = 1, 2, \ldots, n_b)$;

$(\tau\delta)_{ij}$ represents the interaction effect between A and B;

$\in_{ijk}$ represents the random error terms (which are assumed to be normally distributed with a mean of zero and variance of σ^2) and the subscript k denotes the m replicates ($k = 1, 2, \ldots, m$).

Since the effects τ_i , δ_j and $(\tau\delta)_{ij}$ represent deviations from the overall mean, the following constraints exist (equation 2):

$$\sum_{i=1}^{n_a} \tau_i = 0; \sum_{j=1}^{n_b} \delta_j = 0; \sum_{i=1}^{n_a} (\tau\delta)_{ij} = 0;\ \sum_{j=1}^{n_b} (\tau\delta)_{ij} = 0 \tag{2}$$

Hypothesis Tests in General Factorial Experiments

Furthermore, in addition to the two factors A, B, and the interaction between them AB, after building the relationship model (equation 1), it is necessary to check the hypotheses to evaluate their significance in the following aspects.

1. H0: $\tau_1 = \tau_2 = \ldots = \tau_{na} = 0$ (Main effect of A is absent)

   H1: $\tau_I \neq 0$ for at least one i

2. H0: $\delta_1 = \delta_2 = \ldots = \delta_{nb} = 0$ (Main effect of B is absent)

   H1: $\delta_j \neq 0$ for at least one j

3. H0: $(\tau\delta)_{11} = (\tau\delta)_{12} = \ldots = (\tau\delta)_{nanb} = 0$ (Main effect of AB is absent)

   H1: $(\tau\delta)_{Ij} \neq 0$ for at least one ij

The sum of squares of the factors is as follows (equation 3):

$$SS_{TR} = SS_A + SS_B + SS_{AB} \tag{3}$$

where SS_{TR} represents the model sum of squares, SS_A represents the sequential sum of squares due to factor A, SS_B represents the sequential sum of squares due to factor and SS_{AB} represents the sequential sum of squares due to the interaction AB. The mean squares are obtained by dividing the sum of squares by the associated degrees of freedom. Once the mean squares are known the test statistics can be calculated. For example, the test statistic to test the significance of factor A (or the hypothesis H0: $\tau_I = 0$) can then be obtained as (equation 4):

$$(F_0)_A = \frac{MS_A}{MS_E} = \frac{SS_A / dof(SS_A)}{SS_E / dof(SS_E)} \tag{4}$$

Similarly, the test statistic to test significance of factor B and the interaction AB can be respectively obtained as (equation 5 and equation 6):

$$(F_0)_B = \frac{MS_B}{MS_E} = \frac{SS_B / dof(SS_B)}{SS_E / dof(SS_E)} \tag{5}$$

$$(F_0)_{AB} = \frac{MS_{AB}}{MS_E} = \frac{SS_{AB} / dof(SS_{AB})}{SS_E / dof(SS_E)} \tag{6}$$

where MS_A is the mean square for factor A and MS_E is the error mean square, MS_B is the mean square for factor B and MS_E is the error mean square, MS_{AB} is the mean square for interaction AB and MS_E is the error mean square.

It is recommended to conduct the test for interactions before conducting the test for the main effects. This is because, if an interaction is present, then the main effect of the factor depends on the level of the other factors and looking at the main effect is of little value. However, if the interaction is absent then the main effects become important.

2.2. Experimental materials

PC (Portland cement) is crushed from clinker with a certain amount of gypsum (accounting for 4 % – 5 %). Meanwhile, PCB (Portland blended cement) is a mixture of Portland cement produced from grinding a mixture of clinker, gypsum, and additives (the amount of additives including gypsum does not exceed 40 % of which the full additive does not exceed 20 %). PC40 (type 1) and PCB40 (type 2) is one of the common types of cement, with the physical and chemical components that meet the requirements, and both of them having equal strength of 40 Mpa at 28 days of age.

River sand: Natural sand has the largest nominal particle size of 2.5 mm with a density of 2.62 g/cm^3. Although natural sand has mechanical indicators meeting the requirements, but the modulus of size and particle composition shows that this is fine sand leading to the amount of mixed water increasing, so it is necessary to consider mixing with other sands to adjust the modulus of size and particle composition.

Crushed sand produced from rock originated from sedimentary rock. Crushed sand with particles larger than 2.5 mm and 5.0 mm is quite large, with a density of 2.62 g/cm^3, which needs to be mixed with fine sand to have a mixture of small aggregates with large modulus and reasonable grain composition.

Coarse aggregate produced from andesite stone has a particle size of 5 mm – 20 mm, has the largest nominal particle size of 20 mm with a density of 2.72 g/cm^3. Fly ash taken from the silo, and the physical-mechanical properties of fly ash Vung Ang I are in line with the technical requirements of fly ash Type F as prescribed of ASTM C618 [25], which is qualified for use as construction materials.

Superplasticizer additive from O-Basf MasterGlenium® SKY 8735, with a composition consisting of ether polycarboxylates (PCE).

Water meets the standards for concrete production.

2.3. Mix design

Select the percentage of the ratio of crushed sand and river sand is 40:60 used to make concrete to optimizing the amount of binder used. The rate of mixing is commonly used at commercial concrete stations in Vietnam. A small aggregate mixture of 40 % crushed sand and 60 % natural sand has physical-mechanical properties, size modulus, and particle composition suitable for use in the manufacture of concrete.

Research and design of concrete components have a level of strength from 20 MPa to 40 MPa with the workability of 120 mm – 160 mm.

Designing the method of concrete mix, according to the ACI 211.4R [21]. The required average strength is used to select the concrete composition. In the design of materials for the manufacture of concrete mixes, the mineral additives have an essential role that is regulated to use as silica fume or fly ash. Fly ash can be type F or type C. In which, the recommended fly ash content a substitute for cement is class F fly ash about 15 % – 25 %, and fly ash type C about 20 % – 35 %. The amount of water in the mixture is reduced by using a superplasticizer. The concrete mix composition is summarized, as shown in Table 1.

Table 1. Component concrete mix.

No	Concrete of Grade	FA (%)	Type of cement	Cement (kg)	FA (kg)	CA (kg)	RS (kg)	CS (kg)	W (lít)	SP (lít)	W/B
1	20	0	1	260	0	1050	531	354	192	2.86	0.74
2	20	0	2	290	0	1045	531	342	191	3.19	0.66
3	20	5	1	247	13	1050	531	354	191	2.86	0.73
4	20	5	2	275.5	14.5	1045	513	342	191	3.15	0.66
5	20	10	1	234	26	1045	531	354	191	2.84	0.73
6	20	10	2	261	29	1040	513	342	190	3.12	0.66
7	20	15	1	221	39	1045	531	354	190	2.82	0.73
8	20	15	2	246.5	43.5	1040	513	342	190	3.07	0.66
9	20	20	1	208	52	1045	528	352	190	2.82	0.73
10	20	20	2	232.0	58	1040	510	340	189	3.02	0.65
11	30	0	1	360	0	1025	507	338	184	3.96	0.51
12	30	0	2	365	0	1025	498	332	183	4.02	0.50
13	30	5	1	342	18	1020	505	337	184	3.94	0.51
14	30	5	2	346.7	18.3	1020	498	332	183	4.00	0.50
15	30	10	1	324	36	1020	504	336	183	3.92	0.51
16	30	10	2	328.5	36.5	1020	497	331	182	3.98	0.50
17	30	15	1	306	54	1015	504	336	182	3.90	0.51
18	30	15	2	310.2	54.8	1015	497	331	182	3.95	0.50
19	30	20	1	288	72	1010	504	336	182	3.88	0.51
20	30	20	2	292.0	73	1015	495	330	181	3.92	0.50
21	40	0	1	440	0	1005	480	320	180	4.84	0.41
22	40	0	2	455	0	1005	470	313	177	5.01	0.39
23	40	5	1	418	22	1002	480	320	179	4.82	0.41
24	40	5	2	432.3	22.8	1000	470	313	177	4.00	0.39
25	40	10	1	396	44	1000	477	318	179	4.80	0.41
26	40	10	2	409.5	45.5	1000	468	312	176	3.98	0.39
27	40	15	1	374	66	1000	475	317	178	4.78	0.40
28	40	15	2	386.8	68.3	995	468	312	176	3.95	0.39
29	40	20	1	352	88	995	474	316	178	4.75	0.40
30	40	20	2	364	91	990	468	312	175	3.92	0.38

While: FA – Fly Ash; RS – River Sand; CS – Crush Sand; CA – Coarse Aggregate; W – Water; SP – superplasticizer; B – Binder.

2.4. Experiment

The experiment is conducted at the sample ages, as shown in Table 2. The experiment method of compressive strength of concrete was performed according to ASTM C39 [26]. For each concrete at a certain age, an experiment was conducted with three cylindrical prototypes (diameter 150 mm, height 300 mm). The mixture was fabricated by the ASTM C192 [27] and the European standard [22]. The sample is compacted on an automatic vibrator until all air bubbles are released, and the cement paste floats evenly, using a flattened model.

The samples are flattened the contact surface to ensure the compression plate is in contact with the sample surface during the experiment. The compressive intensity experiments of concrete were performed under ASTM C39 [26]. The cylindrical sample experiment with diameter D = 150 mm and height H = 300 mm; Carry out the force load at a maximum velocity of 0.15 – 0.35 MPa/s until sample failure. With each type of concrete conducting experiments, each group includes three compressed samples at the required ages, shown in Fig. 1.

a) Concrete mixer **b) Sample** **c) Moisturizing** **d) Sample compressor**

Figure 1. Some photos of the experiment.

3. Results and Discussion

Based on the Design of Experiments and statistical analysis with Minitab 19 software at 95 % confidence level, significance level α = 5 %. The number of test samples: 3 samples/group ensure to detect the difference within ± 3α. A general full factorial design was used to plan the experiment and analyze the results achieved.

3.1. Experimental results

Using Minitab19 software to design General full factorial design and analyze the results. The input variables of the experimental design: 3 variables

- Concrete grade: There are 3 types: C20, C30, C40.
- Date of age: There are 9 days: 1, 3, 7, 14, 28, 56, 90, 180, 360.
- Fly ash: There are 5 ratios: 0 % (control); 5 %; 10 %; 15 %; 20 %.
- Type of cement: There are 2 types of PC40 (type 1) and PCB40 (type 2).
- Each mixture consists of three specimens.

The output results need statistical analysis of one criterion is the compressive strength R_n. Total number of experiments: 3 × 9 × 5 × 2 × 3 = 810 (specimen), the results are summarized in Table 2.

Table 2. Results of compressive strength.

No	FA(%)	Type of cement	Days	Concrete grade 20			Concrete grade 30			Concrete grade 40		
				1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
1	0	1	1	0	0	0	7.3	7.8	8	11	11.5	10.8
2	0	1	3	15.2	16	15.3	23.3	23.8	23.1	26.4	26.9	26.2
3	0	1	7	22	22.5	21.8	32.4	32.9	32.2	36.9	37	37
4	0	1	14	26	26.5	26.2	38.1	38.6	37.9	45.2	45.7	45
5	0	1	28	30.3	31	31	45.6	46	45.3	55.1	55.6	54.9
6	0	1	56	33.6	34.3	33.8	50.6	51.1	50.4	60.1	60	60
7	0	1	90	35.4	36.2	35.1	52.9	53.4	52.7	62.3	62.8	62.1
8	0	1	180	36.9	37.4	36.7	54.7	55.2	54.5	64.5	65	64.3
9	0	1	360	37	37.5	37.6	55.6	56.1	55.6	66.1	66.6	65.9
10	0	2	1	6.9	7.4	6.7	9	9	8.3	10.9	11.4	11
11	0	2	3	13.7	14.2	13.5	22.7	23.2	22.5	26.2	26.7	26
12	0	2	7	20.3	20.8	20.1	31.7	32.2	31.7	36.6	37.1	36.4
13	0	2	14	24.7	25.2	24.5	37.2	37.7	37	44.8	45	45

No	FA(%)	Type of cement	Days	Concrete grade 20			Concrete grade 30			Concrete grade 40		
				1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
14	0	2	28	29.8	30.3	30	44.6	45.1	44.4	54.6	55.1	54.4
15	0	2	56	32.2	32.7	32	49.1	49.6	48.9	59.5	60	59.3
16	0	2	90	33.1	33.6	33.3	51.3	51.8	51.1	61.7	62.2	61.5
17	0	2	180	34	34.5	33.8	53.5	54	54	63.9	64.4	63.7
18	0	2	360	35.2	35.7	35	55.3	55.8	55.1	65.5	66	65.3
19	5	1	1	0	0	0	6.4	6.9	6.2	10.8	11.3	10.6
20	5	1	3	13.2	13.7	13.2	22.1	22.6	21.9	25.8	26.3	25.6
21	5	1	7	20	20.5	19.8	31.4	31.9	32	36	36.5	36
22	5	1	14	24	24.5	23.8	36.8	36.1	37	44.1	44.6	43.9
23	5	1	28	28.9	29.4	28.7	44.1	44.6	45	53.8	54.3	53.6
24	5	1	56	32.2	32.7	32	49.4	49.9	49.2	59.2	59.7	59
25	5	1	90	33.8	34.3	33.8	51.8	52.3	52	61	61.5	61.8
26	5	1	180	35.6	36.1	35.4	53.8	54.3	53.6	63.2	63.7	63
27	5	1	360	36.2	36.7	36.5	54.4	54.9	54.2	65	65	64.6
28	5	2	1	6.6	7.1	6.4	8.3	8	8.5	10.6	11.1	10.4
29	5	2	3	13.7	14.2	13.5	22.2	22	21.8	25.5	26	25.3
30	5	2	7	19.4	19.9	19.2	30.9	31.4	30.7	35.6	36.1	35.4
31	5	2	14	23.7	24.2	23.5	36.3	36	36.5	43.2	44	43.5
32	5	2	28	28.5	29	28.3	43.5	44	43.5	53.1	53.6	52.9
33	5	2	56	31.1	31.6	30.9	47.9	48.4	47.7	58.4	58.4	59
34	5	2	90	31.9	32.4	31.7	50.2	50.7	51	60.5	61	60.3
35	5	2	180	31.4	32.1	31.9	52.2	52.7	52	62.4	62	62
36	5	2	360	31.9	32.4	31.7	54	54.5	53.8	64	64	63.7
37	10	1	1	0	0	0	5.5	6	5.3	10.4	10.9	10.2
38	10	1	3	10.2	10.7	10	21.6	22.1	21.4	24.9	25.4	25
39	10	1	7	18	18.5	17.8	30.2	30.7	30	34.8	34.5	35
40	10	1	14	22	22.5	21.8	35.4	35.9	35.2	42.6	43	43
41	10	1	28	26.8	27.3	26.6	42.4	42.9	42.2	51.9	52.4	51.7
42	10	1	56	30.2	30.7	30	47.5	48	47.3	58.2	58	57.9
43	10	1	90	31.9	32	32	50	50	49.3	59.9	60.4	59.7
44	10	1	180	33.4	33.9	33.2	52	52.5	51.8	61.8	62.3	61.6
45	10	1	360	34.9	35.4	34.7	52.5	53	52.3	63.3	63.8	63.1
46	10	2	1	6.3	7	6.5	7.6	8.1	7.4	10.4	10.9	10.2
47	10	2	3	12.6	13	12.3	21.4	21.9	21.2	24.9	25.4	24.7
48	10	2	7	18.6	19.1	18.5	30	30.5	29.8	34.7	35.2	35
49	10	2	14	22.7	23.2	22.5	35.2	35.7	35	42.5	43	42.3
50	10	2	28	27.3	27.8	27.1	42.1	42.6	41.9	51.8	52	52
51	10	2	56	29.9	30.4	29.7	46.3	46.8	46.1	57.7	58.2	57.5
52	10	2	90	30.8	31.3	30.6	48.7	49.2	48.5	59.8	60.3	59.6
53	10	2	180	31.7	32.2	31.5	50.5	51	50.3	61.6	62	61.6
54	10	2	360	32.8	33.3	32.6	52.3	52.8	52.1	63.2	63.7	63
55	15	1	1	0	0	0	4.6	5.1	4.4	10	10.5	9.8
56	15	1	3	8.5	9	8.3	20.8	21.3	20.6	24	24.5	23.8
57	15	1	7	16	16.5	15.8	29.2	29.7	29	33.5	34	33.3
58	15	1	14	20	20.5	19.8	34.3	34.8	34.1	41	41.5	40.8
59	15	1	28	24.5	25	24.3	41	41.5	40.8	50	50.5	49.8
60	15	1	56	28.4	28.9	28.2	46.1	46.6	47	56	56.5	56.6
61	15	1	90	30.2	30.7	30	48.8	49.3	49	58.3	58.5	59
62	15	1	180	31.8	32.3	31.6	50.3	50.8	51	60.5	61	60.3

No	FA(%)	Type of cement	Days	Concrete grade 20			Concrete grade 30			Concrete grade 40		
				1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
63	15	1	360	33	33.5	33.2	50.8	51.3	50.6	62.4	62	62.7
64	15	2	1	6	6.5	5.8	6.9	7.4	6.7	9.9	10.4	9.7
65	15	2	3	12	12	11.8	20.5	21	20.3	23.8	24.3	3.6
66	15	2	7	17.7	18.2	17.5	28.7	29.2	28.5	33.2	33.7	33
67	15	2	14	21.4	22	21.6	33.7	33.7	33	41	40.8	41
68	15	2	28	26	26.5	25.8	40.3	40.8	40.1	49.6	50	50
69	15	2	56	28.8	29.3	29	44.3	44.8	44.1	56	56.2	56.6
70	15	2	90	29.9	30.4	29.7	46.7	46.7	47	58.5	59	58.3
71	15	2	180	30.4	30.9	30.2	48.8	49.3	48.6	60.5	61	60.3
72	15	2	360	31.5	32	31.3	50.2	50.7	50	61.9	61.6	61
73	20	1	1	0	0	0	3.7	4.2	3.5	9.7	10	10
74	20	1	3	7	7.5	6.8	20.1	20.6	20	23.3	23.8	24
75	20	1	7	14	14.5	13.8	28.3	28.5	29	32.5	33	32.3
76	20	1	14	18	18.5	17.8	33.1	33	33.5	39.8	40	40
77	20	1	28	22.1	22.6	21.9	39.6	40.1	39.4	48.5	49	48.3
78	20	1	56	26.2	26.7	27	44.7	45.2	44.5	55	54.2	54.8
79	20	1	90	28.6	29.1	28.4	47.1	46.5	45.8	57.1	57.6	56.9
80	20	1	180	30.5	31	30.3	49	49	48.7	60	60.5	59.2
81	20	1	360	31.5	32	31.3	49.1	49	49.3	61.5	62	61.3
82	20	2	1	5.7	6.2	5.5	6.2	6.7	6	9.6	10.1	9.4
83	20	2	3	11.4	11.9	11.2	19.5	20	19.3	23	23.5	22.8
84	20	2	7	16.9	17.4	16.7	27.5	28	27.3	32.1	32.6	33
85	20	2	14	20.6	21.1	20.4	32.2	32.7	32	39.3	39.8	39.1
86	20	2	28	24.8	25.3	24.6	38.5	39	38.3	47.9	48.4	47.7
87	20	2	56	28	28.5	27.8	42.4	42.9	42.2	55	54.6	54.4
88	20	2	90	29	29.5	28.8	44.7	44	43.3	57	57.5	56.8
89	20	2	180	29.5	30	29.3	47	47.5	46.8	58.9	59.4	58.7
90	20	2	360	31	31.5	30.8	48.1	48.6	47.9	61	60.7	60.4

3.2. Discuss the results

The results of the analysis of all variables and interaction between each other affected the compressive strength with statistical significance, shown in Fig. 2.

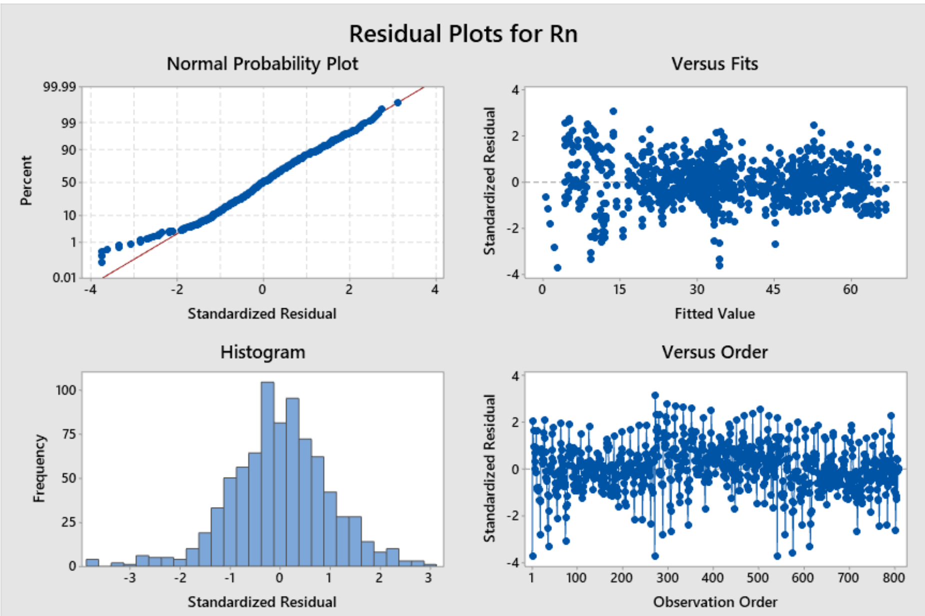


Figure 2. Residual Plots for R_n.

From Fig. 3, The chart evaluating the residuals shows that the normal distribution graph is showing the residuals very close to the normal distribution, and distributed on both sides via the "0" line so satisfying conditions for applying experimental statistical methods.

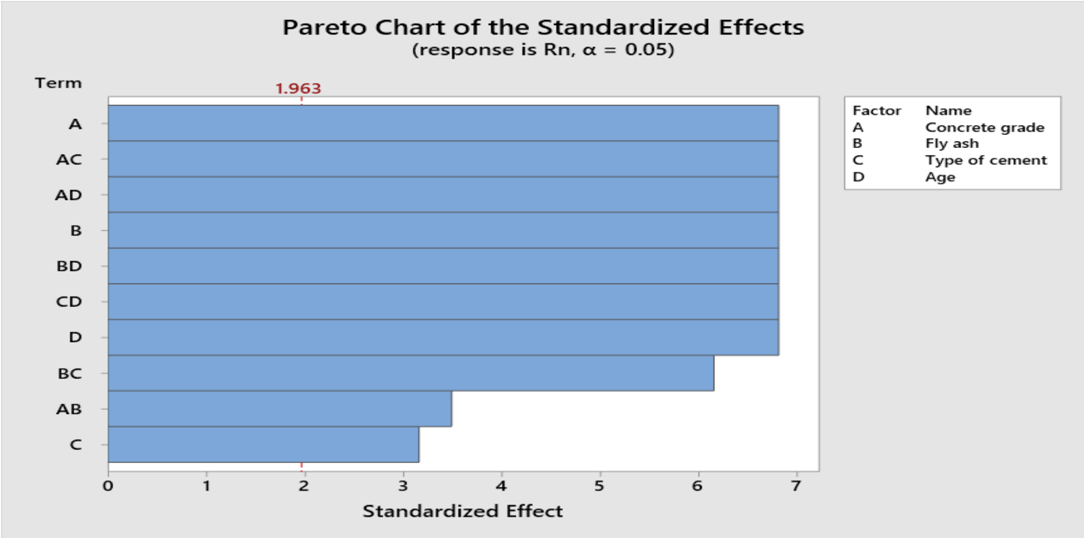


Figure 3. Pareto chart of the factors influencing R_n.

The Pareto chart in Fig. 3 shows that all variables and interactions between variables affect R_n with statistical significance. Cement type (C) has the least impact compared to other factors. Analysis of the variance of factors affecting compressive strength, the relationship model between them is built from Table 3 to Table 5 as follows:

Table 3. Analysis of variance factors and regression model.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	85	235257	2767.7	4597.05	0.000
Linear	15	226674	15111.6	25099.52	0.000
Concrete grade	2	65398	32698.8	54310.95	0.000
Fly ash	4	2543	635.8	1056.09	0.000
Type of cement	1	6	6.0	9.99	0.002
Age	8	158727	19840.9	32954.58	0.000
2-Way Interactions	70	8583	122.6	203.66	0.000
Concrete grade*Fly ash	8	17	2.1	3.53	0.001
Concrete grade*Type of cement	2	50	25.2	41.84	0.000
Concrete grade*Age	16	8013	500.8	831.80	0.000
Fly ash*Type of cement	4	29	7.4	12.25	0.000
Fly ash*Age	32	193	6.0	10.04	0.000
Type of cement*Age	8	280	35.0	58.13	0.000
Error	724	436	0.6		
Lack-of-Fit	184	370	2.0	16.56	0.000
Pure Error	540	66	0.1		
Total	809	235693			

Table 4. Model Summary.

S	R-sq	R-sq(adj)	R-sq(pred)
0.775930	99.82%	99.79%	99.77%

Table 5. Regression Table.

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	35.3156	0.0273	1295.35	0.000	
Concrete grade					
20	–11.8611	0.0386	–307.63	0.000	1.33
30	1.9819	0.0386	51.40	0.000	1.33
Fly ash					
0	2.4530	0.0545	44.99	0.000	1.60
5	1.2807	0.0545	23.49	0.000	1.60
10	0.0715	0.0545	1.31	0.190	1.60
15	–1.2711	0.0545	–23.31	0.000	1.60
Type of cement					
1	0.0862	0.0273	3.16	0.002	1.00
Age					
1	–28.5478	0.0771	–370.21	0.000	1.78
3	–15.8878	0.0771	–206.03	0.000	1.78
7	–7.5456	0.0771	–97.85	0.000	1.78
14	–1.9222	0.0771	–24.93	0.000	1.78
28	5.0533	0.0771	65.53	0.000	1.78
56	9.5933	0.0771	124.41	0.000	1.78
90	11.5311	0.0771	149.54	0.000	1.78
180	13.2644	0.0771	172.01	0.000	1.78
Concrete grade*Fly ash					
20 0	0.1759	0.0771	2.28	0.023	2.13
30 5	0.1904	0.0771	2.47	0.014	2.13
Concrete grade*Type of cement					
20 1	-0.3414	0.0386	-8.85	0.000	1.33
30 1	0.2475	0.0386	6.42	0.000	1.33
Concrete grade*Age					
20 1	8.313	0.109	76.23	0.000	2.37
20 3	4.303	0.109	39.46	0.000	2.37
20 7	2.484	0.109	22.78	0.000	2.37
20 14	0.908	0.109	8.32	0.000	2.37
20 28	–1.458	0.109	–13.37	0.000	2.37
20 56	–2.821	0.109	–25.87	0.000	2.37
20 90	–3.402	0.109	–31.20	0.000	2.37
20 180	–4.069	0.109	–37.31	0.000	2.37
30 1	–2.116	0.109	–19.41	0.000	2.37
30 7	0.431	0.109	3.96	0.000	2.37
30 90	0.365	0.109	3.35	0.001	2.37
30 180	0.751	0.109	6.89	0.000	2.37
Fly ash*Type of cement					
0 1	0.2354	0.0545	4.32	0.000	1.60
5 1	0.2274	0.0545	4.17	0.000	1.60
10 1	-0.1251	0.0545	–2.29	0.022	1.60
15 1	-0.1356	0.0545	–2.49	0.013	1.60
Fly ash*Age					
0 1	-1.610	0.154	–10.44	0.000	2.84
0 3	-0.497	0.154	–3.23	0.001	2.84
0 28	0.684	0.154	4.43	0.000	2.84

Term	Coef	SE Coef	T-Value	P-Value	VIF
0 180	0.356	0.154	2.31	0.021	2.84
5 1	–0.871	0.154	–5.65	0.000	2.84
5 28	0.506	0.154	3.28	0.001	2.84
5 90	0.317	0.154	2.06	0.040	2.84
15 28	–0.403	0.154	–2.62	0.009	2.84
Type of cement*Age					
1 1	–1.4673	0.0771	–19.03	0.000	1.78
1 3	–0.2740	0.0771	–3.55	0.000	1.78
1 56	0.2849	0.0771	3.70	0.000	1.78
1 90	0.4294	0.0771	5.57	0.000	1.78
1 180	0.6272	0.0771	8.13	0.000	1.78

ANOVA analysis results adjusted determination coefficient R-sq(adj) = 99.79 %, all variables and combinations have P-value coefficient < 0.05. The regression table shows the relationship between compressive strength and factors. In which the model takes into account the interaction between the factors. Values that guarantee a significance level with P-value < = 0.05 are retained, while effects that do not guarantee statistical significance are removed in the regression table.

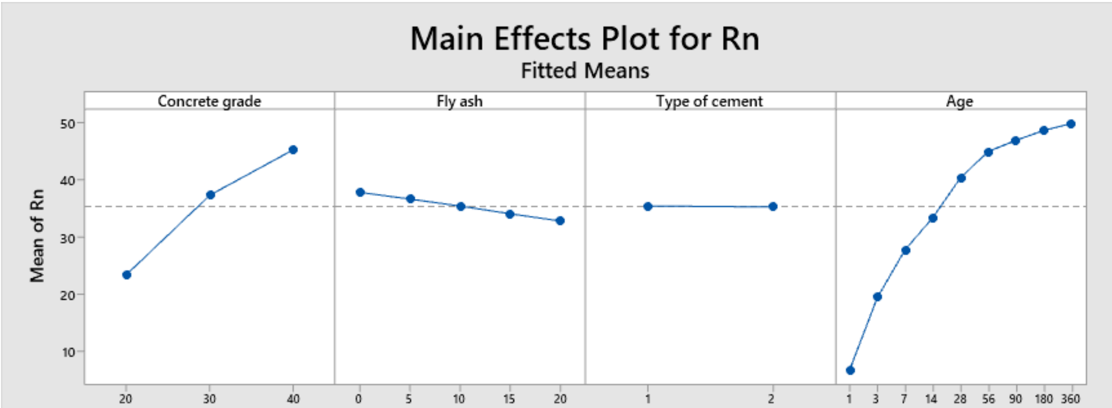


Figure 4. Factors that mainly influence R_n.

Fig. 4 shows the main factors that affect the compressive strength of concrete and their degree of influence. The grade of concrete will affect the design of the components in concrete with the higher the level, the correspondingly high strength. The impact of fly ash tends to the opposite. The more using fly ash, the intensity tends to decrease, while the type of cement has no significant effect between two kinds of cement PC and PCB at the same level. The most significant impact is the age of the concrete. The longer the time, then increasing the intensity of the concrete, the most robust increase in the period from 1 day to 56 days (very steep graph). However, after this period, the uptrend gradually slows down, and from 180 days to 360 days, the level of increase is negligible, the intensity remains at a stable level.

Observed Fig. 5 shows the interaction between the factors affecting the compressive strength of the concrete. The graphs related to the interaction effect between age and other factors have the most apparent change.

The graph in Fig. 6 shows the strength development of fly ash concrete over time; similar to previous studies [16–20], the compressive strength of concrete tends to decrease with increasing content used fly ash. Especially when studying the effect of time on the compress strengthen of fly ash concrete, Tukey's post-deterministic analysis shows very clear subgroups shown in Table 6 and Fig. 7.

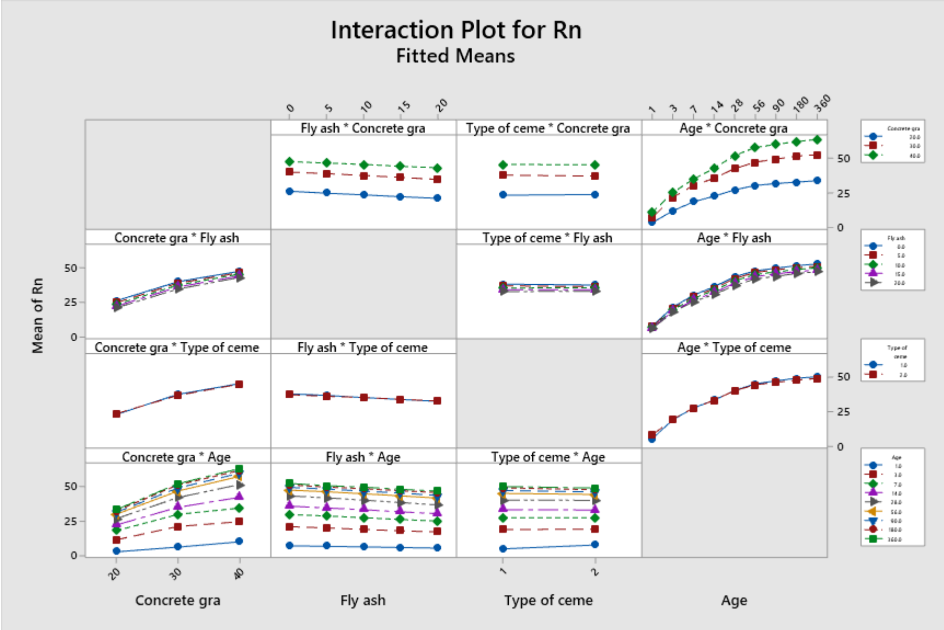


Figure 5. Interaction Plot for R_n.

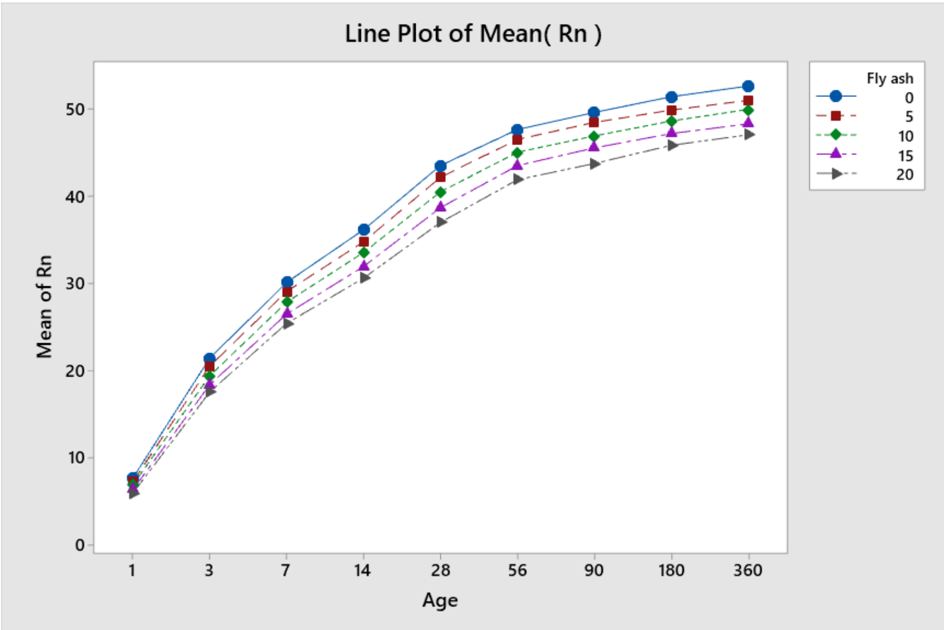


Figure 6. Compression strength development over time.

Table 6. Tukey Pairwise Comparisons between age of fly ash concrete.

Grouping Information Using the Tukey Method and 95 % Confidence

Age	N	Mean	Grouping
360	90	49.78	A
180	90	48.58	A B
90	90	46.85	A B
56	90	44.91	B
28	90	40.37	C
14	90	33.393	D
7	90	27.770	E
3	90	19.428	F
1	90	6.768	G

Means that do not share a letter are significantly different.

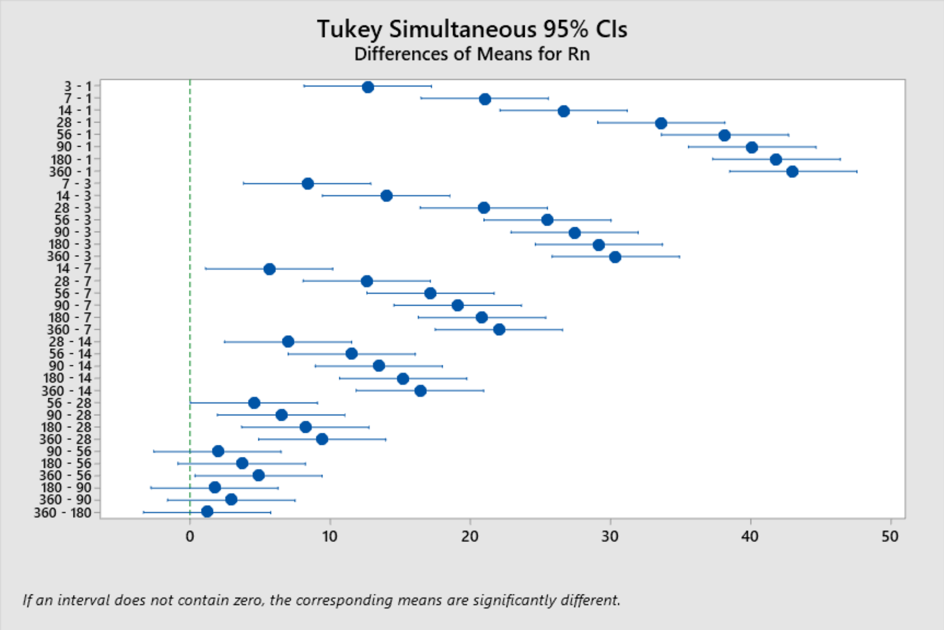


Figure 7. Compression strength development over time.

The difference is most pronounced in the 1, 3, 7, 14, and 28 years old, when they are classified into different groups, G, F, E, D, C, respectively. This marked difference partly reflects the cement's hydration and the reaction of fly ash and the cement's hydration product in the concrete mix. That process simultaneously increases the concrete's consistency, making the concrete's compressive strength increase rapidly, especially after seven days of age. Whereas the 56,90 and 180,360 of the remaining days, the difference between the age dates is classified into two groups A and B, meaning that the change in intensity between the age dates is not significant. These partly explain the intensity stability after the reaction equations occurred; in other words, the intensity developed slowly after 90 days and gradually stabilized at the age of 360 when the increase was not significant.

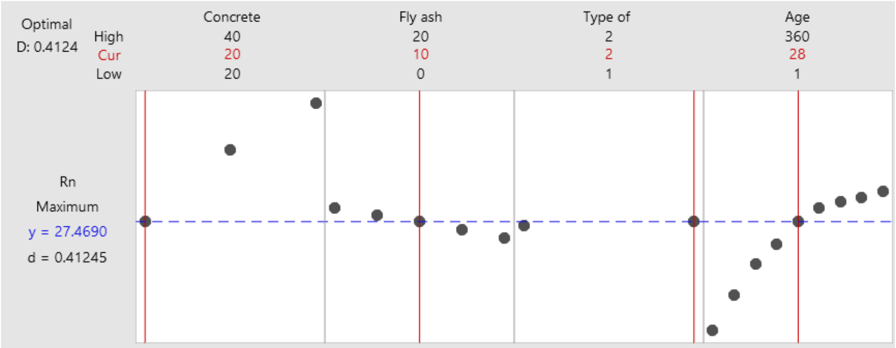
3.3. Response optimization to determine the best possible combinations for each grade of concrete

The most apparent difference between the methods using the experimental DOE planning and linear regression is to give predictive options when there are input parameters and output requirements for the problem.

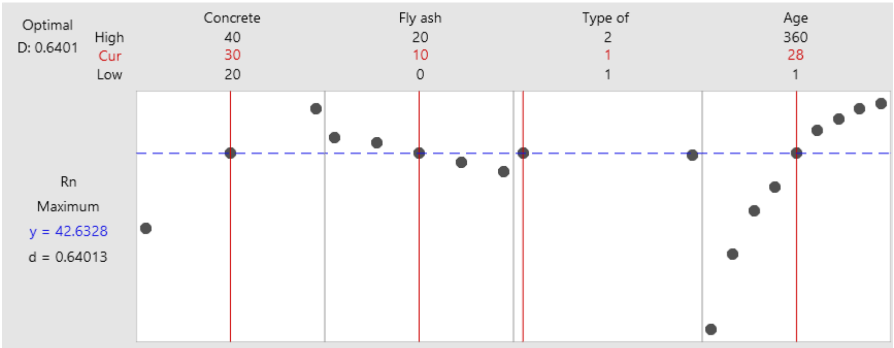
To satisfy each concrete level has the best-guaranteed intensity at 28 days, the options are selected as Table 7 and Fig.8 below.

Table 7. The optimal options for each concrete grade.

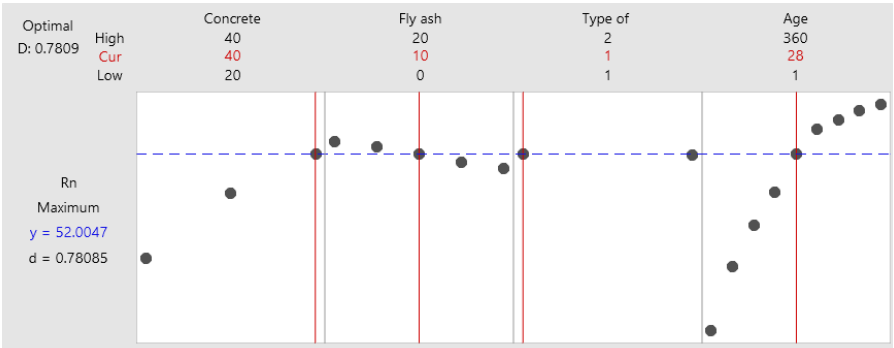
No	Solution	Concrete grade	Fly Ash (%)	Type of cement	Age	Rn Fit	Composite Desirability
1	1	20	10	2	28	27.4690	0.412448
2	2	20	10	1	28	26.7006	0.400910
3	3	20	15	2	28	25.7110	0.386051
4	1	30	10	1	28	42.6328	0.640133
5	2	30	10	2	28	42.2235	0.633986
6	3	30	15	1	28	40.8149	0.612837
7	1	40	10	1	28	52.0047	0.780851
8	2	40	10	2	28	51.9027	0.779320
9	3	40	15	1	28	50.1868	0.753555



a) Optimal D: 0.4124



b) Optimal D: 0.6401



c) Optimal D: 0.7809

Figure 8. The images show the optimal solutions for the respective concrete grades.

For each concrete grade, there are three options, which have been proposed with the amount of fly ash and type of cement, based on ensuring the compressive strength of fly ash concrete at the best level at 28 days. Furthermore, for all three grades of concrete with proposed options for the optimal solution, fly ash content is usually selected at 10 % and 15 %, although in experimental planning, fly ash is considered up to 5 levels ranging from 0 % to 20 %.

4. Conclusions

1. Fly ash cement concrete has been applied in many countries to take advantage of waste from thermal power plants, which improves both the properties of concrete, such as workability, consistency, strength, and increase the intensity remaining to solve problems of environmental pollution. There are many factors to consider affecting the properties of concrete, especially the compressive strength, which is the most fundamental parameter specific to each concrete grade. The covered factors in the paper include the level of concrete, the type of used cement, the percentage of fly ash is used with the total amount of binder, and the time factor.

2. Based on previous studies and the authors' group, fluctuation of selected elements, to meet the current needs of reality. The results show that all factors have an apparent influence on the compressive strength of the concrete, especially the time factor. Over time the vigorous development process is for the first time (from 1 to 56 days). After this period, the process slows down and does not seem to change after one-year-old. At the same time, the conventional and mixed PC cement does not show the difference in the compressive strength of concrete.

3. Besides, the most useful fly ash content for concrete grades to achieve the best compressive strength at 28 days ranges from 10% to 15%. This research result is also consistent with some other studies in the world. Thus, with the influencing factors, depending on the grade of concrete used, the most appropriate coordination options can be selected.

5. Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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