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An assessment of optimal mixture for concrete made with recycled concrete aggregates

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Abstract

Due to a wide range of variability of engineering properties for recycled concrete, in general, a large number of experiments are usually required as to decide a suitable mixture for obtaining the desired requirements for concrete made with recycled concrete coarse/fine aggregate. This article adopts Taguchi's approach with an L_{16} (2^{15}) orthogonal array and two-level factor to reduce the numbers of experiment. Five control factors and four responses (slump and compressive strengths at 7, 14, and 28 days) were used. Using analysis of variance (ANOVA) and significance test with F statistic to check the existence of interaction and level of significance, and computed results of total contribution rate, an optimal mixture of concrete qualifying the desired engineering properties with the recycled concrete aggregates can easily be selected among experiments under consideration.

Keywords: Orthogonal array; Compressive strength; Workability; Concrete

1. Introduction

Recycled concrete aggregate, sometimes referred to as crushed concrete, comes from the demolition of Portland cement concrete elements of buildings, roads, and other infrastructures. Due to the reservation of natural resource, prevention of environmental pollution, and cost-saving consideration of construction project, the recycled concrete aggregate has been widely reused for making different construction materials [1], producing high-strength/high-performance concrete [2], or serving as the base or subbase material in the road construction [3]. Before these demolished debris can be ready for reuse, crushing and screening are required to produce aggregate within the limits of mixing gradation for either Portland cement concrete or bituminous concrete. As a result of crushing, microcracks will remain in recycled concrete aggregate such that much particular attention, for example, high amount of water requirement, smaller specific gravity, and possible reduction in quality and durability, etc., needs to be paid in advance in order for the product to meet the specific required performance. Although some other new techniques had been proposed to produce recycled concrete aggregate with improved quality [4,5], owing to the cost-effective concern and/or other practical consideration, the crushed aggregate is sometimes directly applied for utilization. Besides, since the recycled concrete aggregate is always collected from different sources or types of concrete, the basic engineering properties, such as shape and texture, specific gravity, absorption, moisture content, permeability, strength characteristics, deleterious substance, resistance to freeze–thaw, etc., will vary considerably. As a result, a significant variation on engineering properties of concrete made with recycled concrete aggregate has been reported [6–9]. In Taiwan, it is estimated that more than 640,000 tons of

Table 1
Main control factors and factor levels

Designation	Control factor	Level 1	Level 2
A	water/cement ratio	0.5	0.7
B	volume ratio of recycled coarse aggregate	0.420	0.404
C	replacement by river sand	0%	100%
D	content of crushed brick	5%	0%
E	cleanness of aggregate	as-is	water-washed

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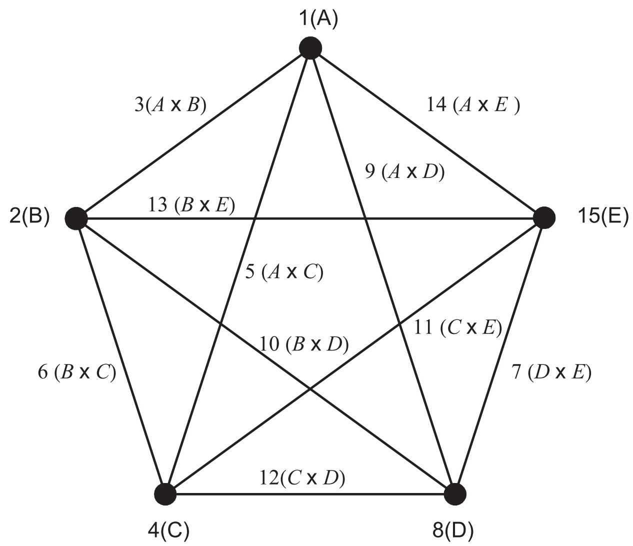

Fig. 1. A linear graph of an L_{16} (2^{15}) orthogonal array.

demolished debris of Portland cement concrete from reinforced concrete buildings and infrastructures has been produced annually. Much of the concrete debris is bonded with brick fragment by mortar. A proper process to reuse the recycled concrete aggregate from this large amount of construction debris is a major issue. In this article, the recycled concrete aggregate for utilization in new concrete is studied, and a statistical and systematic approach is proposed to select the optimal mixture proportioning of concrete based on the requirements on the slump and compressive strengths.

2. Design of experiment

Due to a wide range of variability of mechanical properties for the recycled concrete coarse/fine aggregates, it is usually necessary to carefully plan an experimental design method for obtaining a feasible mixture of concrete made with those aggregates and assessing their impact on the mechanical behavior of the resulting concrete. Normally, a series of tests in which purposeful changes were made to the variables of the concrete mixture was then conducted, so that valid and objective conclusions can be obtained based on the resulting test data. Assume an engineering experiment requires n control factors and two control levels per control factor to understand the influence and interaction of its input data on the output results. By using a traditional experimental process, usually at least all the possible 2^n tests need to be carefully conducted and finished before an optimal performance can be concluded. The number of tests can get very large really fast. To reduce the number of such tedious and costly tests but still be able to maintain an insight into the overall effects of the input factors on the output, a technique based on the design of experiments (DOE) that optimizes the process having controllable inputs and measurable outputs ought to be considered [10]. In this technique, only a few numbers of tests that systematically choose certain combinations of values of those control factors are required, but it is possible to separate their individual effects. The theory behind this technique, which needs to consider both the process of designing the experiment and the way of analyzing statistically the experimental data of response, is based on the usage of the orthogonal array, the analysis of variance (ANOVA), and the significance test with F statistic [11,12].

In this study, based on the test results from some preliminary experimental runs, five control factors, i.e., (1) water/cement ratio, (2) volume ratio of recycled coarse aggregate, (3) replacement of river sand, (4) content of crushed brick, and (5) cleanness of aggregate, which were labeled by A, B, C, D, and E, respectively, and two control levels for each control factor were considered, as shown in Table 1. To reduce the number of tests, an L_{16} (2^{15}) orthogonal array in the Taguchi method that only needs 16 experimental runs to

Table 2
Orthogonal array L_{16} (2^{15}) with factor assignment for the experiments

No.	Test sequence	A	B	A × B	C	A × C	B × C	D × E	D	A × D	B × D	C × E	C × D	B × E	A × E	E	Designation of mixture
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
1	5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	A1B1C1D1E1
2	10	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	A1B1C1D2E2
3	7	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2	A1B1C2D1E2
4	15	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1	A1B1C2D2E1
5	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	A1B2C1D1E2
6	11	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1	A1B2C1D2E1
7	13	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1	A1B2C2D1E1
8	14	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2	A1B2C2D2E2
9	12	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	A2B1C1D1E2
10	6	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1	A2B1C1D2E1
11	2	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1	A2B1C2D1E1
12	16	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2	A2B1C2D2E2
13	3	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	A2B2C1D1E1
14	8	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2	A2B2C1D2E2
15	4	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2	A2B2C2D1E2
16	9	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1	A2B2C2D2E1

Table 3
Average values of mechanical properties of aggregate

Items	Fineness modulus (FM)	Specific gravity (SSD)	Specific gravity (OD)	Water absorption ratio (%)	Abrasion ratio (%)	Soundness (%)
Recycled coarse aggregate	6.75	2.27	2.11	6.99	22.4	17.9
Recycled fine aggregate	3.10	2.25	–	11.9	–	10.8
River sand	3.28	2.68	2.62	2.23	–	–
Crushed brick	6.70	2.12	1.93	9.69	11.18	–

optimize the concrete mixture was adopted [11,12]. Its linear graph and typical tabular form are shown in Fig. 1 and Table 2, respectively. The columns of an orthogonal array correspond to the level of control factors and the orthogonal rows to each experimental run, that is, a specific set of factor levels to be tested. Thus, the subscript of this orthogonal array indicates 16 runs and the quantity in parentheses indicates 15 two-level experimental conditions associated with a full experimental design.

From Table 1, 10 interaction effects, A × B, A × C, A × D, A × E, B × C, B × D, B × E, C × D, C × E, and D × E were also used. Basically, the implication of these 10 interaction effects indicates a mutual interaction among each pair of these 5 two-level factors, which in turn is a rather thoughtful consideration for the first few experimental sets at the very beginning stage of most studies. These factors and interactions need to be assigned to a suitable orthogonal array. The total degrees of freedom required is $5 \times (2-1) + 10 \times (2-1) \times (2-1) = 15$. Hence, an L_{16} (2^{15}) orthogonal array, which has 15 degrees of freedom, is a good choice. To eliminate bias and ensure independence among the experimental observations, which are necessary to warrant the use of statistical methods in experimental design, the randomization for both the allocation of the experimental material and the order in which the individual runs of the experimental are to be performed is required. Therefore, the numbers of the test sequence in column 2 of Table 2 were assigned with the aid of a random digit table.

A five-factor ANOVA for the test data was used in this study. After the ANOVA is completed, the F statistic of any specific control factor A, say F_A, which is defined as the ratio between the sum of variance square for the A control factor and the sum of error variance square, can be obtained. The value of F_A is used for the significance test. The bigger the F_A, the larger the significant influence of control factor A will be. The significance level is divided into two kinds: (1) significant ($\alpha = 5\%$) and (2) very significant ($\alpha = 1\%$) as given by the following Eqs. (1) and (2).

$$F_A \geq F_{0.01,v_1,v_2}: \text{ very significant} \quad (1)$$

$$F_{0.01,v_1,v_2} > F_A \geq F_{0.05,v_1,v_2}: \text{ significant} \quad (2)$$

where v_1 and v_2 are the degrees of freedom. Note that, physically, the value of F statistic represents the ratio of variance explained by control factors to the unexplained variance by errors in the experiment.

3. Experimental program

3.1. Component materials

The constituents of the concrete used in this study included the ASTM C 150 Type I Portland cement, crushed recycled coarse and fine concrete aggregates, river sand, and crushed recycled brick. Mechanical properties of all the

Table 4
Sixteen sets of mixture proportions of concrete (kg/m^3)

No.	Test sequence	Designation of mixture	Cement	Recycled coarse aggregate	Recycled fine aggregate	Crushed brick	Natural sand	Water	Cleanness
1	5	A1B1C1D1E1	404.0	902.9	499.9	73.8	0.0	202.0	as-is
2	10	A1B1C1D2E2	404.0	953.6	528.0	0.0	0.0	202.0	washed
3	7	A1B1C2D1E2	404.0	920.3	0.0	48.4	606.9	202.0	as-is
4	15	A1B1C2D2E1	404.0	953.6	0.0	0.0	628.9	202.0	washed
5	1	A1B2C1D1E2	404.0	868.9	533.6	73.8	0.0	202.0	as-is
6	11	A1B2C1D2E1	404.0	917.7	563.5	0.0	0.0	202.0	washed
7	13	A1B2C2D1E1	404.0	886.9	0.0	46.7	648.7	202.0	as-is
8	14	A1B2C2D2E2	404.0	917.7	0.0	0.0	671.2	202.0	washed
9	12	A2B1C1D1E2	288.6	902.9	578.0	77.9	0.0	202.0	as-is
10	6	A2B1C1D2E1	288.6	953.6	610.4	0.0	0.0	202.0	washed
11	2	A2B1C2D1E1	288.6	922.0	0.0	48.5	703.0	202.0	as-is
12	16	A2B1C2D2E2	288.6	953.6	0.0	0.0	727.1	202.0	washed
13	3	A2B2C1D1E1	288.6	868.9	611.6	77.9	0.0	202.0	as-is
14	8	A2B2C1D2E2	288.6	917.7	646.0	0.0	0.0	202.0	washed
15	4	A2B2C2D1E2	288.6	888.5	0.0	46.8	744.9	202.0	as-is
16	9	A2B2C2D2E1	288.6	917.7	0.0	0.0	769.4	202.0	washed

Table 5
Average values of slumps and compressive strengths for 16 sets of mixture

No.	Test sequence	Designation of mixture	Slump (mm)	Average compressive strength (MPa)		
				7 days	14 days	28 days
1	5	A1B1C1D1E1	175	17.79	20.94	22.91
2	10	A1B1C1D2E2	155	17.54	24.89	25.23
3	7	A1B1C2D1E2	180	18.35	22.04	28.88
4	15	A1B1C2D2E1	180	23.15	25.94	30.17
5	1	A1B2C1D1E2	95	21.96	26.22	29.91
6	11	A1B2C1D2E1	140	17.02	18.92	20.26
7	13	A1B2C2D1E1	105	23.64	29.35	33.60
8	14	A1B2C2D2E2	50	28.35	33.79	36.16
9	12	A2B1C1D1E2	100	13.22	17.17	18.48
10	6	A2B1C1D2E1	200	5.84	7.57	9.74
11	2	A2B1C2D1E1	150	10.53	13.88	17.64
12	16	A2B1C2D2E2	90	21.55	23.99	27.66
13	3	A2B2C1D1E1	160	7.87	9.97	12.92
14	8	A2B2C1D2E2	190	8.76	11.92	14.32
15	4	A2B2C2D1E2	115	11.87	14.63	19.86
1	9	A2B2C2D2E1	160	11.81	16.22	20.42

concrete constituents are shown in Table 3. Except for the relatively higher values of soundness ratios of recycled coarse and fine aggregates of 17.9% and 10.8%, respectively, in Table 3, other mechanical properties of recycled aggregates seem to comply with the code requirements.

The crushed recycled coarse and fine concrete aggregates were generated through the demolition of Portland cement concrete elements of reinforced concrete buildings collected from five different construction sites in Taipei, Taiwan. These concrete rubbles were crushed by a 3/4-in. jaw crusher and then screened to the desired gradation for both coarse and fine aggregates using the conventional sieve analysis process.

3.2. Specimen casting

The ACI 211.1 Standard, "Recommended Practice for Selecting Proportions for Normal Weight Concrete," was used for proportioning the concrete mixtures in this study. Two water/cement ratios of 0.5 and 0.7 were selected, which corresponded to the compressive strengths at 28 days of approximately 33.0 and 20.0 MPa, respectively, by ACI 211.1. By using the different values of control factors in Table 1, the grouping alphanumeric series of designation of mixture in Table 2 and the mechanical properties of concrete constituents in Table 3, 16 sets of mixture proportion of recycled concrete are calculated and shown in Table 4. Cylindrical concrete specimen of ∅ 100 × 200 mm was used for the testing of compressive strengths at 7, 14, and 28 days. After 24 h of concrete casting, the steel module of cylindrical specimens was disassembled and the concrete specimens were stored in limewater until about 1 day before testing. The wet specimen was then left in air to dry for about 24 h before the uniaxial compressive test was performed. Three sets of cylindrical concrete specimen were cast for each group of experiment series. Right after the mixing of concrete constituents, the slump of the fresh concrete was also measured. The sequence of mixing the concrete specimen followed the order given in the column 2 of Tables 4 and 5. The resulting test results for both slumps and compressive strengths are shown in Table 5, in which each number of test data represents an average of three test values.

Table 6
ANOVA for slumps

Factor	T_1	T_2	S_i	v	V	F ratio	rho %	Class	$\bar{x}_1$	$\bar{x}_2$
A × B	1315.0	930.0	9264.06	1	9264.06	59.89	32.86	[a]	164.4	116.3
E	1270.0	975.0	5439.06	1	5439.06	35.16	19.06	[a]	158.8	121.9
C × D	1010.0	1235.0	3164.06	1	3164.06	20.45	10.85	[b]	126.3	154.4
B	1230.0	1015.0	2889.06	1	2889.06	18.68	9.86	[b]	153.8	126.9
C	1215.0	1030.0	2139.06	1	2139.06	13.83	7.16	[b]	151.9	128.8
A × D	1195.0	1050.0	1314.06	1	1314.06	8.49	4.18	[b]	149.4	131.3
B × C	1060.0	1185.0	976.56	1	976.56	6.31	2.96	–	132.5	148.1
D × E	1075.0	1170.0	564.06	1	564.06	3.65	1.48	–	134.4	146.3
A	1080.0	1165.0	451.56	1	451.56	2.92	1.07	–	135.0	145.6
A × C	1080.0	1165.0	451.56	1	451.56	2.92	1.07	–	135.0	145.6
D	1080.0	1165.0	451.56	1	451.56	2.92	1.07	–	135.0	145.6
B × E	1155.0	1090.0	264.06	1	264.06	–	–	–	144.4	136.3
A × E	1095.0	1150.0	189.06	1	189.06	–	–	–	136.9	143.8
B × D	1145.0	1100.0	126.56	1	126.56	–	–	–	143.1	137.5
C × E	1110.0	1135.0	39.06	1	39.06	–	–	–	138.8	141.9
Pooled *e*	4505.0	4475.0	618.75	4	154.69	–	8.37	–	–	–
Total	–	–	2723.44	15	1848.23	–	100	–	–	–

T_1 = sum of values from level 1; T_2 = sum of values from Level 2; $S_i = (1/16)(T_1 - T_2)^2$; v = degree of freedom; V = variance = S_i/v; F ratio = $V/(\text{pooled } e(V))$; rho % = contribution ratio = $(V - v\text{pooled } e(V))/(\text{total}(S_i))$; $F_{0.05,v1,v2} = F_{0.05,1,4} = 7.71$; $F_{0.01,v1,v2} = F_{0.01,1,4} = 21.20$; $\bar{x}_1$ = average of T_1; $\bar{x}_2$ = average of T_2.

Pooled *e* includes sets of (B × E, A × E, B × D, C × E).

[a] Very significant.

[b] Significant.

4. Analysis and discussion

4.1. Analysis of slumps

The ANOVA of slumps is shown in Table 6. Based on the criteria in Eqs. (1) and (2), there are six significant factors, A × B, E, C × D, B, C, and A × D, as shown in Table 6. The Pareto analysis of contribution ratio from ANOVA on slumps is shown in Fig. 2, from which the sum of contribution ratio of these six significant factors is 83.97%. Among these factors, three main control factors, E, B, and C, represent the cleanness of aggregate, volume ratio of recycled coarse aggregate, and replacement by river sand, respectively. Basically, the bigger the slump, the better the workability will be, provided that there is no segregation in the fresh concrete. Hence, from columns 2 and 3 of Table 6, the feasible choice for these three main factors are E1, B1, and C1, respectively. The other three interaction factors, A × B, C × D, and A × D, indicate the interaction among main factors of A, B, C, and D. Therefore, the traditional experiment with one single factor cannot reflect this kind of interaction effect and may result in incorrect conclusion on the material behavior. The analysis of these three interaction effects is given in Table 7 and Fig. 3. It is quite interesting to note that better results for main control factors A and B are A2 and B1 from Table 6. However, the interaction ANOVA by Table 7 and Fig. 3 shows that the best combination for factors A and B is A1B1 rather than A2B1. Similar analyses for interaction effects of C × D and A × D can be made and shown in Table 7 and Fig. 3. By comparing mean values of test results for two levels in Table 7, grouping alphanumeric series of mixture designation in Table 2 and interaction factors in Table 6, the best combinations of five main control factors on account for optimal slump for fresh concrete made with recycled concrete aggregates are A1, B1, E1, C1, and D2. The best combination, using water/cement ratio of 0.5, recycled five-concrete aggregate, as-is recycled aggregates, and 0% crushed brick, will be beneficial in increasing the slump of fresh concrete made with recycled concrete aggregates. The slumps for these fresh recycled concrete range from 110 to 160 mm suitable for most construction jobs.

Table 7
Comparison of interaction factors on slumps in Table 6

	Four sets of slumps (mm)				Average
Combination of A and B					
A1B1	17.5	15.5	18.0	18.0	17.25
A1B2	9.5	14.0	10.5	5.0	9.75
A2B1	10.0	20.0	15.0	9.0	13.50
A2B2	16.0	19.0	11.5	16.0	15.63
Combination of C and D					
C1D1	17.5	9.5	10.0	16.0	13.25
C1D2	15.5	14.0	20.0	19.0	17.13
C2D1	18.0	10.5	15.0	11.5	13.75
C2D2	18.0	5.0	9.0	16.0	12.00
Combination of A and D					
A1D1	17.5	18.0	9.5	10.5	13.88
A1D2	15.5	18.0	14.0	5.0	13.13
A2D1	10.0	15.0	16.0	11.5	13.13
A2D2	20.0	9.0	19.0	16.0	16.00

4.2. Analysis of compressive strength

The ratios of compressive strength development of the recycled concrete for 16 sets of tests are shown in Fig. 4 from Table 5, in which the average values of 0.689 and 0.852 for strengths at 7 and 14 days, respectively, are also given. These two values indicate that the influence of moist curing age on recycled concrete strength is similar to that for normal

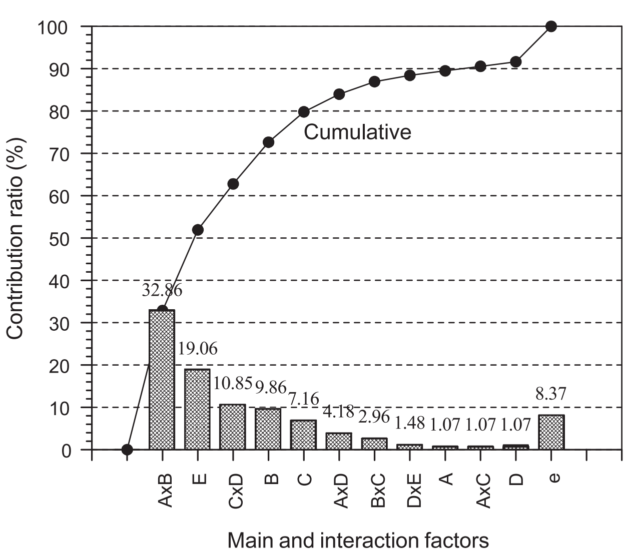

Fig. 2. Pareto analysis of contribution ratio from ANOVA on slumps.

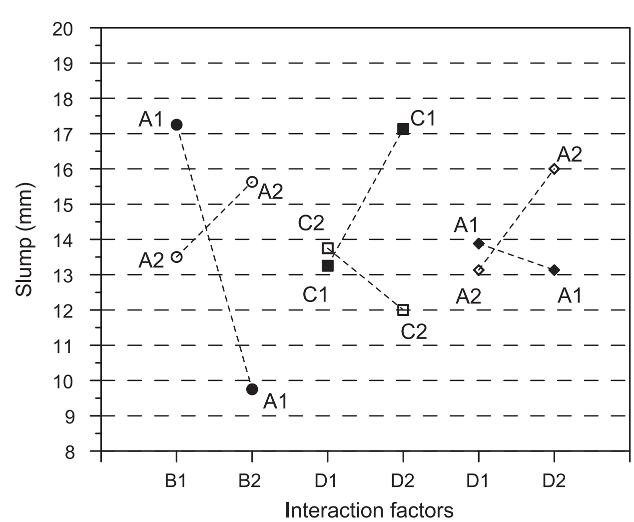

Fig. 3. Response of interaction on compressive strength between A and B, C and D, and A and D.

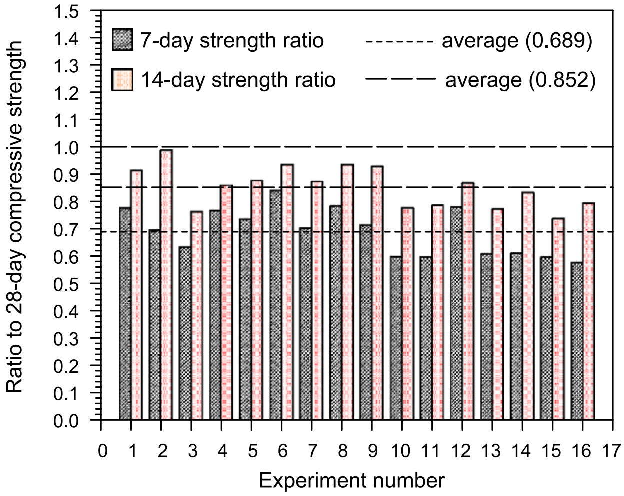

Fig. 4. Ratios of compressive strength development at 7 and 14 days.

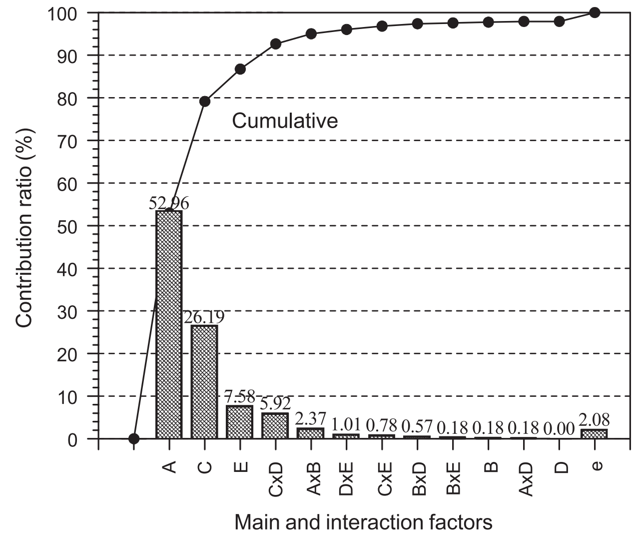

Fig. 5. Pareto analysis of contribution ratio from ANOVA on 28-day compressive strengths.

concrete. Fig. 4 also makes clear that the strength developing speed is faster for recycled concrete with a lower water/cement ration of 0.5. Similar ANOVA can be performed for each of the compressive strengths at 7, 14, and 28 days shown in Table 5. Since the compressive strength of concrete specimen at 28 days is used to serve as a criterion for the quality control, the ANOVA for the 28-day compressive strengths is illustrated in Table 8. Based on the criterion set by Eqs. (1) and (2), there are five significant factors from the analysis in Table 8, A, C, E, C × D, and A × B, that sums up to total ratio of contribution of up to 95.02% as shown in Table 8 and Fig. 5. Among these five significant factors, three main control factors, A, C, and E, bring about 86.74% of contribution ratio, which indicates that the compressive strength of recycled concrete is significantly dominated by the water/cement ratio, amount of replacement with natural river sand, and cleanness of recycled concrete aggregate. From the average values of test data for two control levels as shown in Table 8, the best combination of these three main control factors can be justified as A1 (water/cement ratio of 0.5), C2 (100% of river sand), and E2 (water-washed recycled concrete aggregate). The ANOVA also shows that there are two interaction factors, C × D and A × B, that require further examination to obtain the best combination. The analyses of average values for these two interaction

Table 8
ANOVA for compressive strength at 28 days

Factor	T_1	T_2	S_i	v	V	F ratio	rho %	Class	$\bar{x}_1$	$\bar{x}_2$
A	227.1	141.0	463.11	1	463.11	357.82	52.96	[a]	28.39	17.63
C	153.8	214.4	229.67	1	229.67	177.46	26.19	[a]	19.22	26.80
E	167.7	200.5	67.40	1	67.40	52.08	7.58	[a]	20.96	25.06
C × D	198.6	169.5	52.93	1	52.93	40.89	5.92	[a]	24.83	21.19
A × B	174.7	193.5	21.95	1	21.95	16.96	2.37	[b]	21.84	24.18
D × E	190.4	177.7	10.11	1	10.11	7.81	1.01	–	23.81	22.22
C × E	178.4	189.8	8.09	1	8.09	6.25	0.78	–	22.30	23.72
B × D	179.1	189.1	6.28	1	6.28	4.85	0.57	–	22.38	23.64
B	180.7	187.5	2.84	1	2.84	2.19	0.18	–	22.59	23.43
B × E	180.7	187.5	2.84	1	2.84	2.19	0.18	–	22.59	23.43
A × D	187.4	180.7	2.82	1	2.82	2.18	0.18	–	23.43	22.59
D	184.2	184.0	0.00	1	0.00	0.00	0.00	–	23.03	23.00
A × E	187.3	180.9	2.53	1	2.53	–	–	–	23.41	22.61
B × C	186.4	181.8	1.35	1	1.35	–	–	–	23.30	22.72
A × C	183.9	184.3	0.01	1	0.01	–	–	–	22.99	23.03
Pooled *e*	557.6	546.9	3.88	3	1.29	–	2.08	–	–	–
Total	–	–	871.93	–	–	–	100	–	–	–

Please refer to the notes at the end of Table 6 for definitions of symbols.
$F_{0.05,v1,v2} = F_{0.05,1,3} = 10.13$; $F_{0.01,v1,v2} = F_{0.01,1,3} = 34.12$.
Pooled *e* includes set of (A × C, B × C, A × E).
[a] Very significant.
[b] Significant.

factors are shown in Table 9 and Fig. 6. Therefore, the best combinations can be deduced as C2D2 and A1B2, respectively. To summarize the results, the best combination of these five significant factors is concluded as A1C2E2B2D2, which happens to be the number 8 of the designation of mixture in Table 2 and has the highest average compressive strength of 36.16 MPa as given in Table 5. However, the slump for this designation of mixture has the lowest slump of 50 mm, which implies an unsuitable workability. It is obvious that a specific type of mixture proportioning of recycled concrete is the best under some specified requirement, but may fail in other specified requirements.

4.3. Overall analysis of total ratio of contribution

Due the complexity of constituents, the mechanical properties of recycled concrete are affected by many control factors. It requires quite a lot of time and effort to make the experiments and analyze the test data, such that some specific sound conclusion can be drawn. After achieving some solid conclusions on the best combination of mixture proportioning under different requirements, it is often found that there is contradiction existing among these selected best combinations and apparent interaction effects between main control factors. In practice, it is not possible to just consider the satisfaction at one requirement and ignore other vital requirements. For example, both the workability and compressive strength are strongly desired for most concrete construction, but these two essential criteria are not always satisfied simultaneously as described in the previous section. Further consideration of this issue is definitely necessary.

There are several strategies and targets to make an optimal choice among these possibly contradicting conclusions. For example, the amount of contribution ratio, quality cost, yield efficiency, limitation on the construction period, etc. can be served as a criterion for this purpose. In this study, the cross-table of the ratio of contribution for the characteristics of slump and compressive strength is used as the basic criterion to select the optimal combination. The calculation for such cross-table is shown in Table 10 and the best choice of combination for the mixture of recycled concrete is obtained as A1B1C2D2E1. This best combination corresponds to the number 4 of designation of mixture in Table 5, which has a slump of 180 mm and a compressive strength of 30.17 MPa at 28 days. By examining the values in Table 5, indeed, this designation of mixture seems to be an optimal choice. This optimal designation of mixture can be expressed as follows: "on account of both requirements of higher slump and higher compressive strength at 28 days for the case presented in this study, the optimal mixture for concrete made with recycled aggregates is water/cement ratio of 0.5, volume ratio of recycled coarse aggregate of 42.0%, 100% natural river sand, 0% crushed brick, and as-is recycled aggregate without water-washed aggregate."

From the abovementioned conclusion, it is not surprising to notice that the surface of the as-is recycled aggregate without water-washed aggregate directly taken from the construction sites is usually coated with a thin layer of mud, which indeed helps increase the slump of fresh concrete similar to the function provided by adding the mineral admixture, such as fly ash, slag, silica fume, etc. However, the coating of mud on the surface of aggregate is

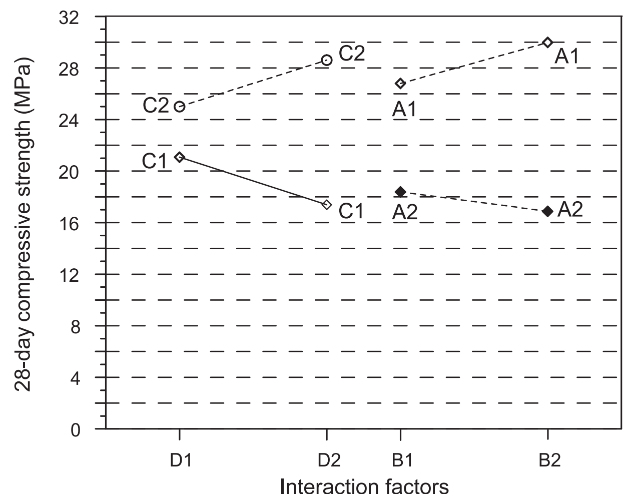

Fig. 6. Response of interaction on compressive strength between C and D and A and B.

Table 9
Comparison of interaction factors on 28-day compressive strengths in Table 8

	Four sets of compressive strengths (MPa)				Average
Combination of C and C					
C1D1	22.91	29.91	18.48	12.92	21.05
C1D2	25.23	20.26	9.74	14.32	17.39
C2D1	28.88	33.60	17.64	19.86	24.99
C2D2	30.17	36.16	27.66	20.42	28.60
Combination of A and B					
A1B1	22.91	25.23	28.88	30.17	26.80
A1B2	29.91	20.26	33.60	36.16	29.98
A2B1	18.48	9.74	17.64	27.66	18.38
A2B2	12.92	14.32	19.86	20.42	16.88

Table 10
Cross-table of the ratio of contribution

No.	A	B	C	D	E
	1	2	4	9	15
Slump	A1	B1	C1	D2	E1
Class of significance		[a]	[a]		[b]
Ratio of contribution (%)	1.07	9.86	7.16	1.07	19.06
Compressive strength at 28 days	A1	B2	C2	D2	E2
Class of significance	[b]		[b]		[b]
Ratio of contribution (%)	52.96	0.18	26.19	0.00	7.58
Contribution at Level 1 (%)	54.03	9.86	7.16	0	19.06
Contribution at Level 2 (%)	0	0.18	26.19	1.07	7.58
Best choice	A1	B1	C2	D2	E1

[a] Significant.
[b] Very significant.

also detrimental to the strength as well as the durability of concrete. For practical application, it is suggested that the recycled concrete aggregates be washed and the regular chemical and mineral admixtures be added into the concrete mix to improve both the strength and durability.

5. Conclusion

In this article, the procedure for assessing the optimal mixture proportioning of concrete made with recycled concrete aggregates based on the orthogonal array, ANOVA, and significance test with F statistic was investigated. The resulting implication of this method was summarized and discussed from the practical point of view. Specific conclusions from the studies can be drawn as follows:

1. The proposed procedure provides a better way for understanding the real engineering behavior of recycled concrete. For example, the ANOVA of slumps shows that, in addition to three main control factors among six significant factors, there are other three interaction factors. The most influential factor is the interaction between water/cement ratio and volume ratio of recycled coarse aggregate rather than anyone of the five main control factors. The ratio for this interaction is as high as 32.86%, which certainly cannot be perceived by other conventional experimental procedures.
2. The proposed procedure also provides a systematic and statistical way for selecting an optimal mixture proportioning. Due to the complexity of physical properties of recycled concrete aggregates, the resulting concrete always exhibits a wide range of variability in engineering properties. Different criteria or requirements always lead to different and sometimes controversial selections for the best-fitted mixture proportioning. The magnitude of the ratio of contribution for each controlling factor calculated by the ANOVA provides a scientific and effective base for making the optimal selection. The advantage for such robust approach may not be quite obvious for simply two requirements of slump and compressive strength as illustrated in this study, but definitely will be very noticeable for the optimal choice among several different criteria.
3. Overall assessment on both slump and compressive strength of concrete indicates that the optimal alphanumeric series of designation of experiment is water/cement ratio of 0.5, volume ratio of coarse aggregate of 42.0%, 100% natural river sand, 0% crushed brick, and as-is recycled aggregate without water-washed aggregate. The resulting concrete has slump of 180 mm and a compressive strength of 30.17 MPa at 28 days, which is applicable for most concrete structures.

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