Optimizing the Concrete Mixture Made with Recycled Aggregate Using Experiment Design

IVANA MILIČEVIĆ, NINA ŠTIRMER, DUBRAVKA BJEGOVIĆ
Faculty of Civil Engineering
Josip Juraj Strossmayer University of Osijek, University of Zagreb
Crkvena 21, Fra Andrije Kačića-Miošića 26
CROATIA
ivanak@gfos.hr http://www.gfos.hr

Abstract: The paper presents the optimization of concrete mixtures made with recycled aggregate. The optimization is defined regarding the concrete properties that could be modeled as second-order functions using response surface method and corresponding experiment designs. Three-level full factorial and fractional factorial designs were compared, as well as central composite designs and Box-Behnken design, regarding the needed number of experiments, i.e. the economic and time constraints.

Key-Words: Concrete, Recycled aggregate, Design of experiment, Factorial designs, Central composite designs, Box-Behnken design

1 Introduction

The use of recycled aggregates (RA) from construction and demolition waste (CDW) in concrete contribute to environmental protection as it reduces the exploitation of natural resources that are limited and can result in considerable savings since it saves the costs of transporting waste to the landfill, and eliminates the cost of disposal. Since aggregates in concrete comprise about 60 to 75 % of the total volume of concrete, any reduction in natural aggregates consumption will have significant impacts in the environment [1]. One of the major components in CDW is concrete rubble that includes concrete materials but can also be mixed with crushed clay bricks. It is technically impossible and not cost effective to separate them [2]. The other type of recycled material that can be used as an aggregate in concrete is waste from the production of ceramic materials such as brick and tiles. Most of this waste type is already incorporated as raw material for new ceramic materials, but part of these wastes and those produced by the construction industry are placed in landfills. The studies in this field showed that some problems arise when using bricks from CDW because of its contamination with mortar, timber and concrete [3]. Debieb and Kenai [4] used coarse and fine crushed bricks and reported a decrease in strength ranging from 20 % to 30 % depending of the degree of substitution. Cachim [1] shows that crushed bricks can be used as natural aggregates substitutes in percentages up to 15 % without strength reduction. For 30 % of natural aggregate substitution, there is a reduction of concrete properties (up to 20 %, depending on the type of brick).

In general, physical and mechanical properties of recycled aggregate depend on waste origin, separation procedures and material treatment. Limiting factors for the practical application of recycled aggregate obtained from demolition of concrete structures are higher water absorption, higher porosity and weaker interfacial zone between recycled aggregate and new cement mortar. Pores and cracks in old cement mortar can significantly affect the mechanical and durability properties of new concrete composites. There are many unsolved problems encountered in controlling the quality of RAC, which include low compressive strength, wide variability of quality, high drying shrinkage, large creep and low elastic modulus [3]. Consequently, most studies recommend a limit of 30 % of RA as substitution of natural aggregate. Many researchers have successfully applied RA on pavement and roadwork or simple structures, underground structures, foundations, piles and mass concrete. However, use of recycled aggregates in higher grade concrete is not common [3]. These weaknesses of RA, including high porosity, high amount of cracks, high level of sulphate and chloride contents, high level of impurity and high cement mortar remains, will affect the mechanical performance of recycled aggregate concrete. To achieve desired properties of recycled aggregate concrete, it is necessary to improve recycling process regarding aggregate

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grading and to research the most suitable combination of natural and recycled aggregate in concrete for certain application.

In order to optimize the concrete mixture it is necessary to obtain basic properties of concrete mixtures produced for varied amounts of concrete components that are supposed to be significant for the concrete mixture optimization.

Each property will be optimized using the response surface method to obtain second-order model:

$$y = \beta_0 + \sum_i \beta_i x_i + \sum_{i<j}\sum \beta_{ij} x_i x_j + \sum_i \beta_{ii} x_i^2 \quad (1)$$

where response y is the particular concrete property, factor values x are the concrete components and parameters β should be calculated fitting the experimental data. Afterwards, the concrete mixture will be optimized employing the multi-criteria decision-making by overlaying the contour plots based on second-order models of particular properties.

In order to obtain the second-order model it is necessary to use three-level experiment designs at least. Namely, two-level experiments allow the fitting of only first-order models with or without interaction terms and cannot detect curvature [5]. Therefore three-level full factorial and fractional factorial designs will be considered, as well as central composite designs and Box-Behnken design [6]. The designs will be compared regarding the feasibility of experiment regarding the economic and time constraints.

2 Comparison of Experiment Designs

Experimental designs are used so that the experiments are defined in an organized manner and allow statistical analysis to be carried out on the resulting data, as it is shown in various areas of engineering [7-9]. The purpose of the analysis would be the evaluation of the second-order model of particular concrete property.

2.1 Full Factorial Design

A full factorial design (Full FD) is the most complete design for a particular factor level. However, it also demands a high number of experiments:

$$\text{number of experiments} = k^n \quad (2)$$

where n is the number of factors, and k is the number of factor levels.

In a case that a full number of experiments cannot be carried out because of economic, time, or other constraints, a fractional factorial design could be used.

2.2 Fractional Factorial Design

Fractional factorial design (Fractional FD) comprises an assumption that some effects are confounded with one another [5]. Thereby the effect is defined as a change in the average response between two factor–level combinations or between two experimental conditions, and confounding when one or more effects that cannot unambiguously be attributed to a single factor or interaction, i.e. two or more experimental effects are confounded (aliased) if their calculated values can only be attributed to their combined influence on the response and not to their unique individual influences.

In Fractional FD effects of primary interest should be unconfounded with other effects or confounded with effects that have negligible impact on experiment results. Researcher, prior to the realization of experiment, should know which effects are confounded.

Fractional factorial experiments are specified by first stating the defining contrast I. The defining contrast I is the generator of this particular fraction [6].

For instance, to implement three-level fractional factorial experiment with three factors A, B and C, it is necessary to designate the levels x_1, x_2 and x_3 of each factor A, B and C, respectively, as 0, 1, or 2, and to determine defining contrast I. For instance, one could choose the defining contrast

$$I = AB^2C \quad (3)$$

Then experimenter can randomly select the fraction from following options:

$$x_1 + 2x_2 + x_3 = 0 \bmod (3), \quad (4a)$$

$$x_1 + 2x_2 + x_3 = 1 \bmod (3) \text{ or} \quad (4b)$$

$$x_1 + 2x_2 + x_3 = 2 \bmod (3). \quad (4c)$$

and carry out the experiments which satisfy the chosen Eqn(4) regarding the levels x_1, x_2 and x_3 of parameters A, B and C, respectively. Applying the defining contrast, Eqn(3), the number of experiments decreases in comparison to full FD, Eqn(2):

$$\text{number of experiments} = k^{n-1} \quad (5)$$

Each additional defining contrast decreases the number of experiments at the same way:

$$\text{number of experiments} = k^{n-m} \quad (6)$$

where m is the number of defining contrasts.

2.3 Designs for Fitting Response Surfaces

Full FD and fractional FD could be used for fitting response surfaces. However, these designs are note rotatable. Rotatable designs estimate the response with equal precision at all points in the factor space that are equidistant from the centre of the design [5], i.e. a design is rotatable if the prediction variance depends only on the distance of the design point from the centre of the design [10].

Rotatability is a desirable property for response-surface models because prior to the collection of data and the fitting of the response surface, the orientation of the design with respect to the surface is unknown.

Two designs that make more efficient use of the experimental units or test runs than the three-level factorial experiments are the central composite design (CCD) and the Box–Behnken (BB) design. Both of these designs require enough observations only to estimate the second-order effects of the response surface, using three or five levels for each factor, but not using all combinations of levels. Both of these designs are rotatable at least approximately.

Central composite designs consists (CCD) of a factorial design (the corners of a cube) together with center and star points [10], Fig. 1, that allow for estimation of second-order effects. For a full quadratic model with n factors, CCDs specify 2^n + $2n$ + 1 design points. The type of CCD used (the position of the factorial and star points) is determined by the number of factors and by the desired properties of the design.

Basic central composite designs are:

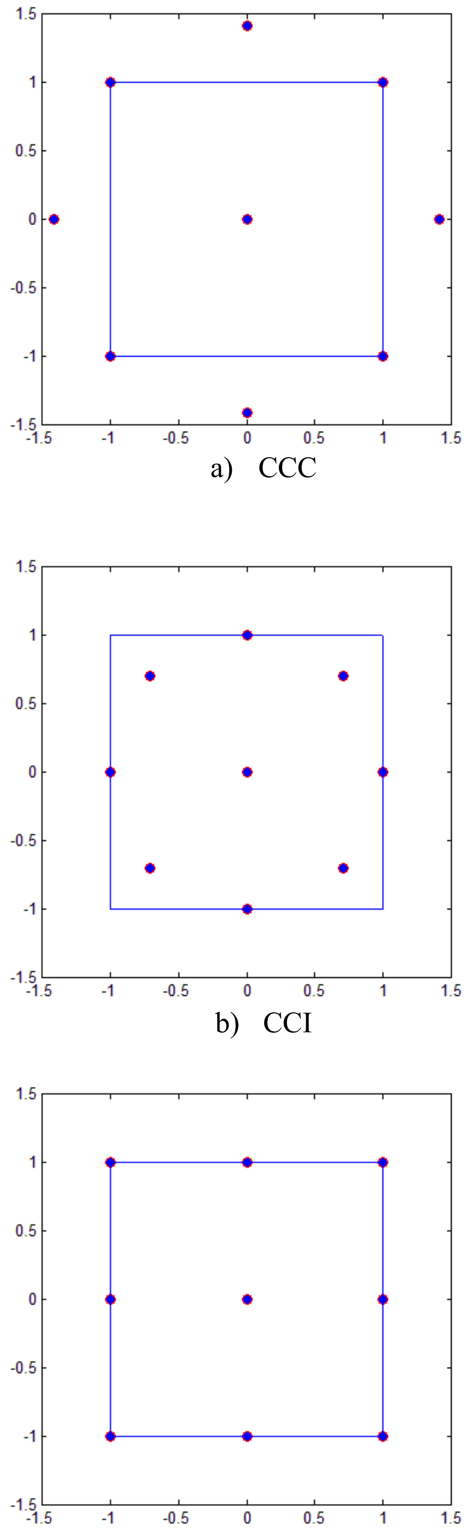
- Circumscribed (CCC) with factor levels ($-\alpha$, -1, 0, 1, α), Fig. 1a
- Inscribed (CCI) with factor levels (-1, - $1/\alpha$, 0, $1/\alpha$, 1), Fig. 1b
- Faced (CCF) with factor levels (-1, 0, 1), Fig. 1c

where α is determined by [6]:

$$\alpha = \sqrt[4]{2^n} \qquad (7)$$

Box-Behnken design is rotatable and, by avoiding the corners of the design space, it allows experimenters to work around extreme factor combinations. The Box-Behnken design does not contain an embedded factorial or fractional FD. A Box-Behnken design requires $2k(k-1)+1$ experiments and the factors are examined at three levels (–1, 0, +1), Fig. 2.

Table 1 summarizes some important properties of designs for fitting response surfaces.



a) CCC

b) CCI

c) CCF

Figure 1 Example of central composite designs (n = 2)

Table 1: Important properties of experiment designs

Design	Factor levels	Number of experiments	Rotatable	Properties
CCC	$-\alpha$, -1, 0, 1, α	$2^n + 2n + 1$	Yes	Good over entire design space
CCI	-1, $-1/\alpha$, 0, $1/\alpha$, 1		No	Good over central subset of design space
CCF	-1, 0, 1		No	Fair ove entire design space, poor for pure quadratic coefficients
BB	-1, 0, 1	N = 2f(f – 1) + 1	Yes	Like an inscribed CCD, however, extremes are then poorly esimated.

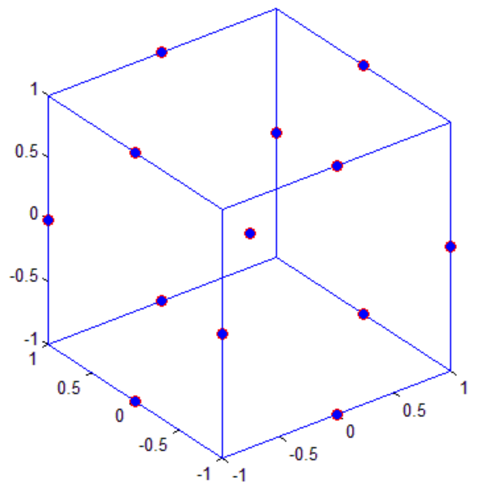


Figure 2 Example of Box-Behnken design (n=3)

3 Usage of Experiment Design

Table 2 shows basic properties for recycled aggregate concrete, number of mixture samples needed for the testing (row "Number") and the costs of testing based on average price in testing laboratories in Croatia (row "costs").

Costs of material and production of mixture samples as well as the cost of working hours needed for production can be estimated from number of needed samples, Table 2, to the total amount of about 210€ which results with total costs of testing of one concrete mixture of about:

$$210€ + 5915€ = 6125€.$$

Factors supposed to be significant for the concrete mixture optimization and, thus, used in experiment designs are: cement, water/cement ratio, air entraining admixture, water reducing admixture percentage of natural aggregate and percentage of recycled aggregate made from crushed brick (recycled aggregate type I) for fraction 0-4 mm and fraction 4-16 mm. Range of variation of each factor is shown in Table 3. Thereby the lower and upper limits correspond to factor levels $-\alpha$ and α for Circumscribed CCD only. For all other designs lower and upper limits correspond to factor levels -1 and 1, respectively. All other used factor levels can be easily calculated using defined upper and lower factor levels.

Table 2: Testing the properties of concrete

Property	**density**	**porosity**	**workability**	**compressive strength**	**flexural strength**	**water absorption**	**drying shrinkage**
Number	0[1]			3	3	0 (3)[2]	3
Costs	10 €	20 €	10 €	60 €	60 €	225 €	900 €
Property	**creep**	**elastic modulus**	**abrasion resistance**	**thermal conductivity**	**fire resistance**	**freezing/ thawing resistance**	**Total**
Number	3	6	1 series	2	30	3	
Costs	1200 €	600 €	130 €	750 €	1200 €	750 €	5915 €

[1] Tests are carried out on fresh concrete mixtures.
[2] Tests are carried out on samples that are used for further tests as well.

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Table 3: Factor limits

Factor	Concrete components	Lower limit	Upper limit
Factor 1	Cement (kg)	300	400
Factor 2	W/C	0,15	0,60
Factor 3	Natural aggregate for fraction 0-4 mm (%)	0	100
Factor 4	Recycled aggregate type I for fraction 0-4 mm (%)	0	100
Factor 5	Natural aggregate, for fraction 4-16 mm (%)	0	100
Factor 6	Recycled aggregate type I, for fraction 4-16 mm (%)	0	100
Factor 7	Air entraining admixture (%)	0,01	0,05
Factor 8	Water reducing admixture (%)	0,5	0,8

Recycled aggregate made from crushed tile (recycled aggregate type II) is also used in mixtures, but its percentage RAII% depends on percentages of used natural aggregate NA% and recycled aggregate type I, RAI%:

$$RAII\% = 100\% - NA\% - RAI\% \quad (8)$$

and therefore recycled aggregate type II is not a factor. Furthermore, the percentage of natural aggregate and recycled aggregate type I must be limited as follows:

$$NA\% + RAI\% \leq 100\% \quad (9)$$

Full FD and fractional FD obviously have significantly higher number of experiments in a comparison to central composite designs and Box-Behnken design, with or without taking the Eqn(9) into account, Table 4.

As above-mentioned, one mixture requires approximately 6125€ costs. A simple calculus reveals that the most of presented experimental designs are not feasible for eight factors in general. Therefore, in future only Box-Behnken experimental design will be considered for research of optimal mixture of concrete made with recycled aggregate.

Table 5 shows some of experiments defined by Box-Behnken design. Thereby, marked rows are not feasible according to (9) and they decrease the number of experiments, Table 4.

Costs of experiment carried out regarding the Box-Behnken design would be approximately 6125€*88 = 539000€ and they could be decreased by omitting some of tests listed in Table 2. For instance, density, porosity, workability, compressive strength and flexural strength could be carried out

Table 4: Number of experiments

	Full FD	Fractional FD	CCC	CCI	CCF	BB
Number of experiments	6561	2187	273	273	273	113
Number of experiments with (9)	$(3^6)*6=4374$	$(3^5)*6=1458$	271	271	207	88

Table 5: Some of experiments defined by Box-Behnken design

Number of experiment	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8
1	300	0,15	50	50	50	50	0,03	0,65
2	300	0,6	50	50	50	50	0,03	0,65
3	400	0,15	50	50	50	50	0,03	0,65
4	400	0,6	50	50	50	50	0,03	0,65
5	300	0,375	0	50	50	50	0,03	0,65
6	300	0,375	100	50	50	50	0,03	0,65
7	400	0,375	0	50	50	50	0,03	0,65
...	...	...	...	...	...	...	...	...
108	350	0,375	50	50	50	100	0,03	0,8
109	350	0,375	50	50	50	50	0,01	0,5
110	350	0,375	50	50	50	50	0,01	0,8
111	350	0,375	50	50	50	50	0,05	0,5
112	350	0,375	50	50	50	50	0,05	0,8
113	350	0,375	50	50	50	50	0,03	0,65

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for each of 88 mixtures (cost of tests per one mixture would be 160€). Afterwards, remaining tests could be carried out on mixtures that are optimal regarding these five properties (cost of tests per one mixture would be 5755€). In this case, costs of material and production, including the cost of working hours equal about 11 € per one mixture. Conclusively, in a comparison to the costs of 539000€ total costs would be decreased significantly:

160 €*88 + 5755€*5 + 11€*(88+5) = 43878€.

4 Conclusion

The use of recycled aggregates from construction and demolition waste in concrete contributes to environmental protection. However, concrete mixtures must be optimized regarding their properties. The economic and time constraints limit the number of experiments which are used to optimize the mixture. To define which experiments should be carried out, it is recommended to apply experiment design which enables a statistical analysis of resulting models. In order to obtain second-order model it is necessary to use three-level experiment designs at least. Thus, three-level full and fractional factorial designs were considered as well as central composite designs and Box-Behnken design. Comparison of needed number of experiments results with the recommendation that the Box-Behnken design should be used. Thereby, the design should be used to obtain models of basic concrete properties only, e.g. density, porosity, etc. Remaining properties, e.g. drying shrinkage, creep, etc., should be obtained carrying out the experiments on mixtures that are optimal regarding the basic properties. At this way the number of experiments could be decreased additionally if needed.

References:

[1] P. B. Cachim, Mechanical properties of brick aggregate concrete, Construction and Building Materials 23 (2009) 1292–1297

[2] J. Yang, Q. Du, Y. Bao, Concrete with recycled concrete aggregate and crushed clay bricks, Construction and Building Materials 25 (2011) 1935–1945

[3] V. W. Y. Tam, X. F. Gao, C. M. Tam, Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach, Cement and Concrete Research 35 (2005) 1195– 1203

[4] F. Debieb and S. Kenai, The use of coarse and fine crushed bricks as aggregate in concrete. Construction and Building Materials 22 (2008) 886–893

[5] R. L. Mason, R. F. Gunst, J. L. Hess, *Statistical Design and Analysis of Experiments*, John Wiley & Sons, Inc., 2003.

[6] D.C. Montgomery, *Analysis of Experiments, fifth edition*, John Wiley & Sons, Inc., 2001.

[7] R.C. Berredo, L.N. Canha, P.Ya. Ekel,L.C.A. Ferreira and M.V.C. Maciel, Experimental Design and Models of Power System Optimization and Control, *WSEAS Transactions on Systems and Control*, Vol. 3, No.1, 2008, pp. 40-49

[8] Lj. Lazić, N. E Mastorakis, Integrated Intelligent Modeling, Simulation and Design of Experiments for Software Testing Process, *Latest Trends on Computers (Volume II),14th International Conference on Computers*, 2010, pp. 555-567

[9] E. Briano, C. Caballini, P. Giribone, R. Revetria, Design of Experiment and Montecarlo Simulation as Support for Gas Turbine Power Plant Availabilty Estimation, *Proceedings of the 12th WSEAS International Conference on Automatic Control, Modelling & Simulation*, 2010, pp. 223-230

[10] Product Help, Matlab, Version 7.7.0.471 (R2008b), September 17, 2008

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