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تصميم تجربة التطبيق لتحسين نسبة استخدام المواد الخام من البوليمر الخرسانة المركبة

بارس سيمسيك* وتايفون أويغونوغلو**

* قسم الهندسة الكيميائية، كلية الهندسة، جامعة كانكري كاراتكين، 18200، كانكري، تركيا.

** قسم الهندسة المدنية، كلية الهندسة، جامعة أفيون كوكاتيب، 03200، أفيون، تركيا.

الخلاصة

وتستخدم تقنيات التحسين على نطاق واسع لحفظ المواد الخام والحصول على عملية التصنيع في الظروف المثلى. وقد تم تنفيذ البرمجة غير الخطية التي تقوم على منهجية سطح الاستجابة بهدف تحديد فعالية التطبيق الأمثل الثاني والنسب المخلوطة المثلى للمركبات الخرسانة البوليميرية. وقد تم اختيار البوليمرات التي حصلت على أعلى التباين على خصائص الخرسانة البوليمر المركبة مثل الحرارية والميكانيكية وقابلية التشغيل كما البولي بروبيلين، اللدائن الحرارية وثنائي ميثيل تيريفثالات الذي يأخذ في أول تطبيق الاستجابة متعددة الاستجابة. وقد تم الحصول على الخرسانة البوليميرية مختلطة (W / m* K 0.63) قيمة التوصيل الحراري التي يتم الحصول عليها مع دراسة التحسين على مرحلتين يتم تضمينها في فئة (C 25 / 30) قوة الضغط كما أنها حصلت على 28 يوما قوة الضغط في 27.27 ميغا باسكال القيمة. عندما يقارن ذلك مع الدراسات في الأدب، فقد حصلت على انخفاض قيمة التوصيل الحراري في قوة الضغط العالي. وأظهرت النتائج أن خطوتين متعددة الاستجابة الأمثل منهجية فعالة جدا لإنتاج الخرسانة التي حصلت على الخصائص المطلوبة باستخدام أقل المواد الخام. وتشير هذه النتائج أيضا إلى أن تأثير التفاعل ينبغي أن يؤخذ في الاعتبار.

A design of experiment application to improve raw materials utilization ratio of polymer concrete composites

Barış Şimşek* and Tayfun Uygunoğlu**

**Department of Chemical Engineering, Faculty of Engineering, Çankırı Karatekin University, 18200 Çankırı, Turkey*

***Department of Civil Engineering, Faculty of Engineering, Afyon Kocatepe University,03200 Afyon, Turkey*

**Corresponding Author: barissimsek@karatekin.edu.tr*

ABSTRACT

Optimization techniques are widely used to save raw materials and to maintain the manufacturing process in optimum conditions. The non-linear programming, which is based on the response surface methodology, has been implemented with the aim of determining the effectiveness of the second optimization application and optimum mix proportions of polymer concrete composites. Polymers, which have got the highest variance on polymer concrete composites' properties such as thermal, mechanical, and workable, have been selected as polypropylene, thermoplastic elastomer, and dimethyl terephthalate that take into account the first multi-response optimization application. The polymer-mixed concrete has got 0.63 W/m*K thermal conductivity value, which is obtained with the two-stage optimization study included in C 25/30 compressive strength class as it has got 28-day compressive strength at 27.27 MPa value. When it is compared to the studies in the literature, it has got the lower thermal conductivity value at the higher compressive strength. The results show that the two-step multi-response optimization methodology is quite effective in producing concrete, which has got the desired properties by using fewer raw materials. These results also indicate that the interaction effect should be taken into consideration.

Keywords: industrial application; polymer composites; raw materials saving; two-step multi-response optimization; thermal properties.

INTRODUCTION

In the field of civil engineering, polymers have become more attractive materials in terms of low thermal conductivity and water permeability features (Heidari-Rarani *et al.*, 2014; Zhao *et al.*, 2016). Properties of polymer concrete composites (POCOM) such as fracture toughness (Heidari-Rarani *et al.*, 2014),mechanical strength (Elalaoui *et al.*, 2012), [3]compressive and flexural strength (Saribiyik *et al.*, 2013), thermal expansion (Ribeiro *et al.*, 2003), chemical resistance (Ribeiro *et al.*, 2002), flow ability (Khalid *et al.*, 2016), deformation ratio (Yeon *et al.*, 2014), compressive and tensile strength (Ahn *et al.*, 2016; Toufigh *et al.*, 2016), impact resistance (Mastali *et al.*, 2016), and mechanical properties (Jeon *et al.*, 2015; Şahmaran *et al.*, 2008) have been analyzed by the researchers in the last decades. Many of the researchers havefocused on evaluating or analyzing the polymers' effect on thermal, mechanical, fluidity, or chemical resistance. Some of the studies, which include the optimization application, are those done on the mechanical and workability properties of polycarbonate and polyethylene terephthalate reinforced concrete (Hannawi *et al.*, 2010), mechanical properties of concrete containing methyl methacrylate (Tanyildizi and Şahin, 2015), polyester reinforcement polymer concrete formulation(Haddad and Al Kobaisi, 2012), and rubberized concrete properties (Vieira *et al.*, 2010).

Polymers in concrete are preferred because they provide thermal insulation in terms of providing energy saving and water resistance and also they reduce the compressive strength of the concrete. The desired level of heat insulation on an acceptable level of compressive strength has been achieved as the multi-response optimization methods can be used to solve the conflicting situation.

Multi-response optimization methodology-based design of experiment (DoE) has the systematic implementation steps. Determining the optimal mix proportions of polymer composite concrete (POCOM), which uses DoE, is crucial to the utilization of resources efficiently. Thus, raw materials saving and sustainable production can be achieved.

There are numerous multi-response optimization methods based on the design of experiment (DoE) that is used to improve raw materials utilization rate. Some of them can be outlined as multi-criteria decision making (MCDM) methods that are often used with the Taguchi design and linear/ nonlinear programming or desirability function approach, which is often used with response surface and full factorial design. MCDM methods such as TOPSIS (Technique of Ordering Preferences by Similarity to Ideal Solutions) have been used to optimize the properties of polymer blended concrete (Şimşek and Uygunoğlu, 2016), process parameters of metal matrix composite (Bhuyan *et al.*, 2015), surface roughness and tool wear (Ramesh *et al.*, 2016), and a refrigerant to air multi-pass louvered fin and flat tube condenser(Shojaeefard and Zare, 2016); GRA (Grey Relationship Analysis) has been also used to optimize the concrete properties,which contain recycled aggregates (Chang *et al.*, 2011),the surface integrity, material removal rate (Goswami and Kumar, 2014), the flow parameters in a heat exchanger tube (Chamoliet al., 2016), and the fabrication parameters of oleo hydrophobic cotton (Ahmad *et al.*, 2016); VIKOR (Vlse Kriterijumska Optimizacija I Kompromisno Resenje) and AHP (Analytic hierarchy process) have been also used to optimize the supply chain management system (Akman, 2015) and outsourcing vendor performance (Sivakumar *et al.*, 2015) with Taguchi method. In a similar way, the linear programming,which is based on the Taguchi models,has been used to optimize electricity monitoring system (Wang *et al.*, 2016), water management system (Wang and Huang, 2015), and credit limit allocation (İç, 2012); the non-linear programming, which is based on response methodology, has been used to optimize the drug release process and gelatins kinetics (Nha *et al.*, 2013) and the normal weight concrete (Şimşek *et al.*, 2014); the desirability function approach has been also used to optimize the performance of self-compacting concrete reinforced with hybrid steel micro-fibers (Ghafariet al., 2014), normal weight concrete properties (Şimşeket al., 2016), machining parameters in turning of polyoxymethylene polymer (Chabbi *et al.*, 2016), and the synthesis of chiral 1,3-oxathiolane by the Trichosporon laibachii lipase (Zhang *et al.*, 2016).

However, all of these studies have a one-stage optimization application. In all of the optimization studies, the product recovery, which occurs in a single stage, has been contented. Polymers in concrete are preferred because they provide thermal insulation in terms of providing energy saving and water resistance and also they reduce the compressive strength of the concrete. Reaching the desired level of heat insulation on an acceptable level of compressive strength has been achieved as the multi-stage optimization methods can be used to solve the conflicting situation. The necessity and success of the second optimization practices, namely, the multi-stage optimization practices, are firstly discussed in the literature mentioned in this study. Thus, it is aimed at having more accurate optimum levels, which means raw material saving. Furthermore, the response surface methodology is very important in exposing binary interactions among polymers. In pilot experiments that have got too many factors, the designs such as the Taguchi method that takes only linear effects into consideration can be used to reduce the number of experiments. However, in the product development studies beyond the pilot experiment, the Taguchi method has a massive disadvantage in not taking interaction effects into consideration.

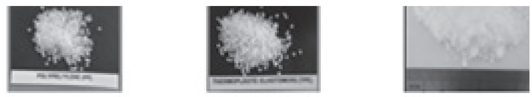
Moreover, when the Taguchi method is only used, many factors can be optimized at the same time with a small number of experiments (e.g., thirteen factors can be optimized with 27 experiments with the use of L27 orthogonal arrays). But, the Taguchi method does not take into account the interaction effects of factors. When the response surface methodology (RSM) is only used, the interaction effects of factors can be evaluated and optimized by the nonlinear models. But, the numbers of factors are increased, and the number of experiments is increased exponentially (e.g., ten factors can be optimized with 170 experiments with the use of Box-Behnken). To overcome this conflicting problem, an integrated multi-response and stage optimization methodology contains the Taguchi method, and the response surface methodology has been firstly applied for optimization problems, which include many factors. This study provides information for researchers and manufacturers about how to implement the two-stage multi-response optimization application with few experiments.

Within this scope, the cement dosage, fly ash content, water to binder ratio, super plasticizer content %, fine aggregate to total aggregate ratio, and coarse aggregate (I) to total aggregate ratio have been fixed according to the first multi-response optimization results (Şimşek and Uygunoğlu, 2016). Factors and their levels, which are used in the second stage multi-response optimization study, have been selected taking into account the first optimization results (Şimşek and Uygunoğlu, 2016). The non-linear programming (NLP),which is based on response surface methodology, has been implemented with the aim of determining the effectiveness of the second optimization application.

Materials and Method

Materials

The optimum parameters for cement dosage, fly ash amount, water to binder ratio, super plasticizer content %, fine aggregate to total aggregate ratio, and coarse aggregate (I) to total aggregate ratio have been found to be 450 kg, 120 kg, 0.46, 1.05, 0.50, and 0.20 (Şimşek and Uygunoğlu, 2016). Therefore, these factors have been fixed in this study at these values according to the first optimization results (L27 design). The MasterGlenium®150 super plasticizer (SP) has been supplied with BASF ®. The SP has been used in all concrete mixtures. The fine aggregate with a size smaller than 4 mm, the coarse aggregate (I) with a size between 4 mm and 11 mm, and the coarse aggregate (II) with a size between 11 mm and 22 mm have been used in the concrete mixtures. The fine and coarse aggregates have specific gravities of 2.71 and 2.87 and mean water absorptions of 1.51% and 0.95 %, respectively.



Properties of polymers	Values		
	PP	TPE	DMT
Melting flow rate, g/10dk 220°C'de	0.905	12-20	-
Density, g/cm^3	230-260	1.20	1.2
COOH end groups, kg/ton	280	-	-
Tensile strength at break, MPa	6	300	-
Elongation at break, %	91	850	-
Melting point, °C	<4 mm	205-215	142
Granules space, G/100 granule	<4 mm	2.5 ± 0.25	<1 mm

Figure 1. Properties of selected polymers for the second optimization application.

Methodology

The following steps, which include the two-stage multi-response optimization, have been used to determine the optimal mix proportions of the POCOM. In the first stage, polypropylene, thermoplastic elastomer, and dimethyl terephthalate, which are replaced in the fine aggregate, has been selected as the most influential factors with effect on POCOM properties according to TOPSIS based Taguchi optimization results (Şimşek and Uygunoğlu, 2016).

Nine quality criteria have been selected as follows: thermal conductivity, 3-day compressive strength, 7-day compressive strength, 28-day compressive strength, slump flow value, the percentage of water absorption, the 28-day splitting tensile strength, the production cost, and water permeability of POCOM concrete properties. In the second stage, optimal mixture levels of POCOM have been determined by RSM based NLP.

Lastly, the statistical analysis has been carried out with the use of variance analysis, main effect, and surface plots.

Empirical Modeling

POCOM characteristics

The first quality criterion of POCOM has been selected to be the thermal conductivity, which provides a thermal comfort for residence and energy savings for manufacturers (Şimşek and Uygunoğlu, 2016). The determination of POCOM's thermal conductivity has been performed by the hot wire method taking into account the ASTM C 1113 standards (Institute, 2013; Şimşek and Uygunoğlu, 2016).

EN 123903/ has been used in the determination of 3-day, 7-day, and 28-daycompressive strength of POCOM (Institute, 2010b). EN 123906/ has been also used in the determination of 28-daysplitting tensile strength of POCOM (Institute, 2010c). EN 123502-(Institute, 2010a), EN 123907- (Institute, 2010d), and EN 12390–8 have been used to determine the slump flow value, the percentage of water absorption, and water permeability ofPOMCO, respectively.

Seven performance criteria and their desired properties are presented in Table 3. All experiments have been implemented on 150x150x150 mm cubic samples. The purchase price of PP, TPE, DMT, cement, fly ash, water, superplasticizer, fine aggregate, and coarse aggregate materials is 2.301 $/kg, 4.845 $/kg, 1.490 $/kg, 0.07 $/kg, 0.03 $/kg, 0.003 $/kg, 2.0 $/kg, 0.050 $/kg, and 0.045 $/kg, respectively.The production costs for all experiment runs are calculated and shown in Table 4.

Table1. POCOM characteristics.

Quality criteria	Exemplar	Definition	Type of concrete test	Desired properties
1	R1	Thermal conductivity (W/m K)	Hardened concrete test	Minimize
2	R2	Compressive strength (N/mm^2) 3-day	Hardened concrete test	Maximize
3	R3	Compressive strength (N/mm^2) 7-day	Hardened concrete test	Maximize
4	R4	Compressive strength (N/mm^2) 28-day	Hardened concrete test	Maximize
5	R5	Slump flow (cm)	Fresh concrete test	Maximize
6	R6	Splitting tensile strength (N/mm^2) 28-day	Hardened concrete test	Maximize
7	R7	Water absorption (%)	Hardened concrete test	Minimize
8	R8	Production cost ($/m^2)	Hardened concrete test	Minimize
9	R9	Water permeability (cm)	Hardened concrete test	Minimize

Definition of factors and experiment conditions

Three factors, with each having five mix levels' effect on the POCOM quality, have been determined to be the amount of polypropylene, thermoplastic elastomer, and dimethyl terephthalate. Such plastic aggregates, which are symbolized with PP, TPE, and DMT, have been used instead of the fine aggregate.

Table 2. Factors and their levels.

Factors	Definition	Bounds* (kg)				
		First bound	Second bound	Third bound	Fourth bound	Fifth bound
PP	Polypropylene	29	43.5	58	72.5	87
TPE	Thermoplastic elastomer	29	43.5	58	72.5	87
DMT	Dimethyl terephthalate	29	43.5	58	72.5	87

*Defined according to the first optimization results.

Response surface design and experimental results

A response surface methodology, which is based on the central composite design (CCD) has been chosen to implement the experiments in this study. In Table 3, columns 24- represent the three control factors and their uncodified levels. Columns 4 and 5 illustrate the dry and wet unit weight of POCOM in all experiments. The concrete temperature of all samples has been given in Table 3, column 7.

Table 3. Response surface methodology-based central composite design.

Exp. No.	Factors (coded)			Factors (uncodified)			Properties of sample		
	PP (kg)	TPE (kg)	DMT (kg)	PP (kg)	TPE (kg)	DMT (kg)	Wet unit weight (g)	Dry unit weight (g)	Concrete temperature °C
M0	-	-	-	-	-	-	8164	7999	23.0
MR1	-1	-1	-1	43.5	43.5	43.5	7246	7099	23.6
MR2	1	1	-1	72.5	72.5	43.5	6850	6729	23.0
MR3	1	-1	1	72.5	43.5	72.5	7032	6873	23.5
MR4	-1	1	1	43.5	72.5	72.5	6963	6822	23.1
MR5	0	0	0	58	58	58	7051	6887	23.4
MR6	0	0	0	58	58	58	7054	6895	23.3
MR7	1	-1	-1	72.5	43.5	43.5	7047	6890	23.2
MR8	-1	1	-1	43.5	72.5	43.5	7168	6988	23.6
MR9	-1	-1	1	43.5	43.5	72.5	7006	6810	23.7
MR10	1	1	1	72.5	72.5	72.5	6880	6688	23.8
MR11	0	0	0	58	58	58	7081	6883	23.8
MR12	0	0	0	58	58	58	7098	6884	23.9
MR13	-2	0	0	29	58	58	7159	7071	24.0
MR14	2	0	0	87	58	58	7021	6908	24.1
MR15	0	-2	0	58	29	58	7200	7165	23.8
MR16	0	2	0	58	87	58	7130	7083	23.7
MR17	0	0	-2	58	58	29	7434	7411	23.9
MR18	0	0	2	58	58	87	7169	7047	22.1
MR19	0	0	0	58	58	58	7091	6885	21.8
MR20	0	0	0	58	58	58	7100	6879	23.8

The experiments have been performed according to RSM based CCD and the results are shown in Table 4.

Table 4. Experimental results.

Exp. No.	R1 (W/m*K)	R2 (N/mm^2)	R3 (N/mm^2)	R4 (N/mm^2)	R5 (cm)	R6 (%)	R7 (N/mm^2)	R8 ($/ m^3)	R9 (cm)
M0*	1.66	44.40	50.40	60.90	16	2.02	4.00	119.70	0.70
MR1	0.87	28.06	33.56	35.60	16	2.03	2.48	478.26	1.56
MR2	0.77	25.60	27.51	30.41	16	1.77	2.12	677.81	2.46
MR3	0.76	21.64	35.14	36.70	17	2.26	2.02	580.52	2.00
MR4	0.89	23.74	24.38	31.94	17	2.02	2.55	654.28	3.48
MR5	0.87	23.20	26.59	32.40	17	2.33	2.81	591.05	1.88
MR6	0.89	23.00	27.00	32.00	17	2.30	2.80	591.05	1.86
MR7	0.84	23.69	27.12	29.60	16	2.23	2.81	321.08	1.94
MR8	0.93	24.36	27.73	32.84	17	2.51	2.87	605.60	2.46
MR9	0.95	21.84	26.80	31.70	16	2.80	2.64	508.30	1.74
MR10	0.73	23.38	26.13	28.10	18	2.79	2.33	718.45	1.68
MR11	0.88	23.10	26.87	32.10	17	2.20	2.84	591.05	1.84
MR12	0.89	23.00	27.20	32.20	17	2.21	2.81	591.05	1.86
MR13	1.05	26.97	29.00	32.58	16	1.23	2.50	522.86	3.04
MR14	0.63	19.47	23.94	26.10	18	1.61	2.87	659.24	1.58
MR15	0.93	24.96	28.10	30.70	17	0.49	3.06	449.09	4.34
MR16	0.74	22.00	32.40	33.40	19	0.66	2.87	733.00	2.27
MR17	0.85	27.24	30.10	32.84	16	0.31	2.80	546.39	2.55
MR18	0.66	21.04	25.20	26.00	16	1.70	2.28	635.70	8.78
MR19	0.89	23.80	27.30	33.00	17	2.25	2.81	591.05	1.90
MR20	0.90	24.00	28.00	32.30	17	2.32	2.83	591.05	1.85

*Reference concrete.

Non-linear regression and meta-models

The results of variance analysis have been given in Table 5. The useful models have been determined at 0.05 significant levels.

Table 5. Analysis of variance for responses.

The source of variance	Responses (p value)								
	R1	R2	R3	R4	R5	R6	R7	R8	R9
Model	0.001*	0.001*	0.438	0.000*	0.005*	0.491	0.607	0.000*	0.019*
Linear	0.087	0.010*	0.658	0.697	0.558	0.503	0.539	0.000*	0.501
Quadratic	0.036*	0.587	0.501	0.001*	0.008*	0.144	0.372	1.000	0.012*
Interaction	0.499	0.023*	0.232	0.171	0.131	0.977	0.731	0.549	0.521

*significant at 95% confidence level.

As the p values are smaller than 0.05 (%95 confidence interval), which is given in Table 5 and the regression coefficient, R^2, is larger than 75.0 in Table 6, it can be said that the meta-models for thermal conductivity, 3-day and 28-daycompressive strength, slump flow, production cost, and water permeability have been found important for the optimization stage. The non-linear useful meta-models have been obtained with the use of Minitab® version 15 and are shown in Table 6.

Table 6. Non-linear models obtained by RSM design.

Quality criteria	Regression equations(analysis in uncodified factors)	R^2, %
1	R1 = -0.073+(0.0088*PP)+(0.0106*TPE)+(0.0238*DMT)-(0.00005*PP^2)-(0.00006*TPE^2)-(0.000151*DMT^2)-(0.000059*PP*TPE)-(0.000095*PP*DMT)-(0.000048*TPE*DMT)	89.60‡
2	R2 = 72.324-(0.4505*PP)-(0.4206*TPE)-(0.6235*DMT)+(0.0009*PP^2)+(0.0002*TPE^2)+(0.0009*DMT^2)+(0.002*PP*TPE)+(0.0028*PP*DMT)+(0.0045*TPE*DMT)	89.34‡
4	R4 = 31.8618-(0.121*PP)-(0.0109*TPE)+(0.1171*DMT)-(0.0034*PP^2)+(0.0009*TPE^2)-(0.0027*DMT^2)-(0.0004*PP*TPE)+(0.003*PP*DMT)-(0.0011*TPE*DMT)	94.25‡
5	R5 = 17.5455-(0.0286*PP)-(0.0889*TPE)+(0.0317*DMT)-(0.0002*PP^2)+(0.001*TPE^2)-(0.0014*DMT^2)-(0.0006*PP*TPE)+(0.0018*PP*DMT)+(0.0006*TPE*DMT)	84.65‡
8	R8 = 586.866+(40.522*PP)+(166.975*TPE)+(69.678*DMT)-(8.367*PP^2)-(8.372*TPE^2)-(8.372*DMT^2)+(100.670*PP*TPE)+(110.680*PP*DMT)-(100.08*TPE*DMT)	89.89‡
9	R9 = 6.40477+(0.10529*PP)-(0.08617*TPE)-(0.20453*DMT)+(0.00016*PP^2)+(0.00134*TPE^2)+(0.00415*DMT^2)-(0.0002*PP*TPE)-(0.0024*PP*DMT)-(0.00125*TPE*DMT)	78.73‡

‡useful models.

Validation of non-linear meta-models

The experimental data of responses versus the predicted responses are plotted in Figure 2 as the real and predictive values, respectively. The correlation between real and predictive data has been analyzed with the use of the graphics. It can be said that there is good consistence between the real and predictive values (R2 vales have been found to be 0.956, 0.927, 0.929, 0.872, and 0.937 for thermal conductivity, 3-day compressive strength, 28-day compressive strength, slump flow value, and the water permeability, respectively). Optimization application can be performed with these models because it has high consistence.

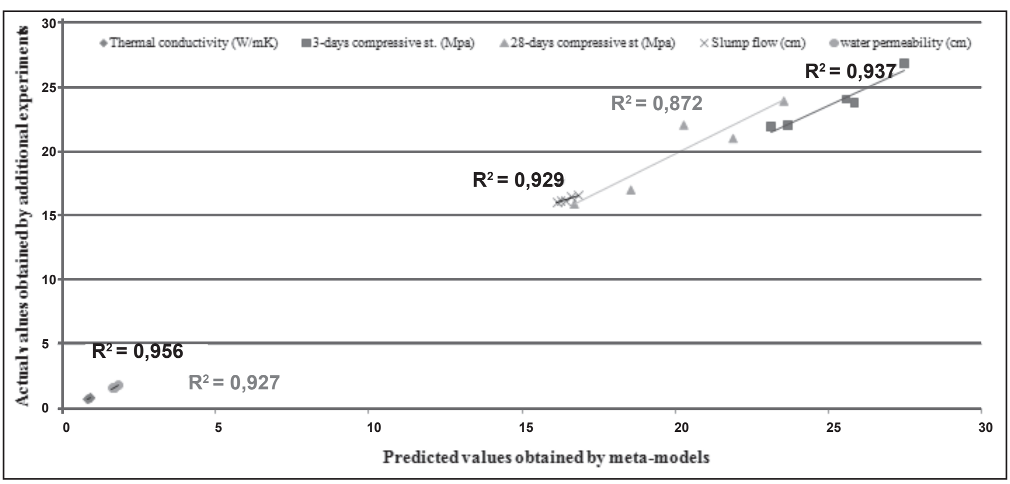


Figure 2. The predicted values plotted against the actual values for responses.

Surface plots for POCOM

The changing in response, which depends on the factors PP, TPE, and DMT, can be examined with the use of 3D plots. As shown in Figure 3, the response surface plots of all responses give an unchanging point. Therefore, the surface plots, which have saddle behavior, have been drawn in Figure 3.

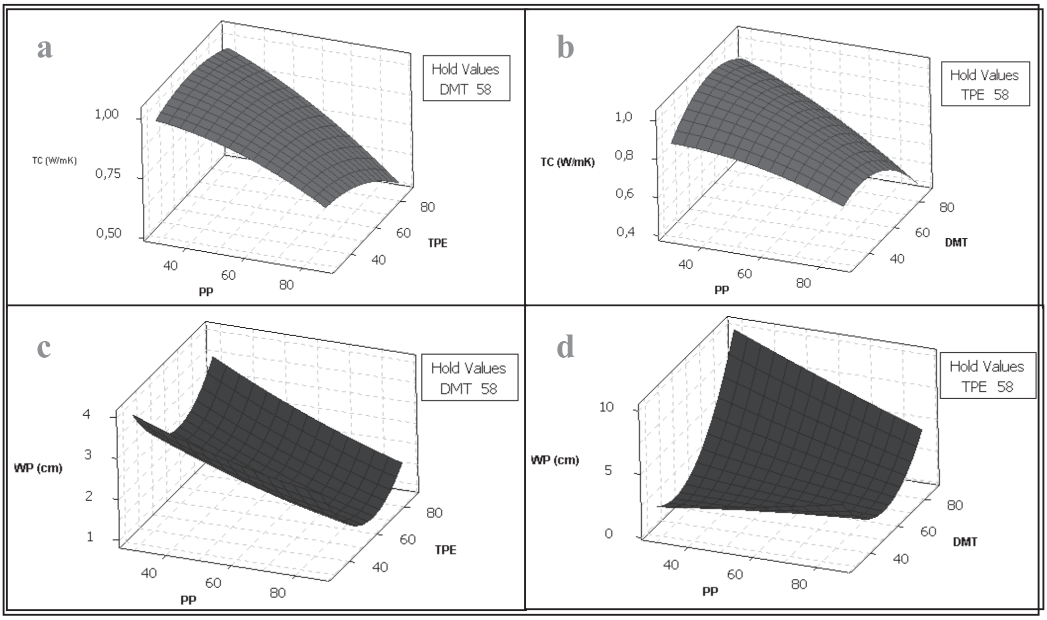


Figure 3. Surface plots of thermal conductivity (in red) and water permeability (in blue) in encoded values: (a) fixed DMT at 63 kg, (b) fixed TPE at 58 kg, (c) fixed DMT at 63 kg, and (d) fixed TPE at 58 kg.

MULTI-RESPONSE OPTIMIZATION

Nonlinear programming

The useful models, in other words, the objects' functions have been selected as thermal conductivity (R1), 3-day compressive strength (R2), 28-day compressive strength (R4), slump flow value (R5), production cost (R8), and the water permeability (R9) according to the regression coefficient (R2) (please see Table 6). The same weight has been designated to these responses. Constrains' functions have been determined as $40 \leq PP \leq 90$, $40 \leq TPE \leq 90$, and $40 \leq DMT \leq 90$. The optimal mixture rates for the minimization of thermal conductivity, production cost, water permeability, the maximization of 3-day compressive strength, 28-day compressive strength, and slump flow value have been determined to be PP=80, TPE=40, and DMT=80 kg by nonlinear programming with the use of MATLAB® software version 2015a.

Validation experiment

In order to validate the optimum results, an experiment has been performed for PP=80, TPE=40, and DMT=80 kg via MATLAB® code built for NLP. The paired t-test's results support that the optimum mix design has been carried out successfully (Table 7) (Şimşek *et al.*, 2016).

Table 7. Paired t-test results for validation optimum mix ratios.

Responses	Symbols	Predicted values	Validation experiment	Difference (d)	Mean, $\bar{d}$	Standard deviation	*t*,Test statistics‡	$T_{5;0.95}$ ($t_{n-1,1-\alpha}$)
1	R1	0.625	0.63	-0.005	3.24	7.217	*1.099	2.571
2	R2	20.14	19.5	0.64				
3	R4	27.27	27.0	0.27				
4	R5	17.12	17	0.12				
5	R8	617.664	599.7	17.964				
6	R9	4.75	4.3	0.45				
Toplam	n=6							

*Null hypothesis H0= the Xi's are interdependent and there is no difference between the optimum levels obtained by validation experiment and meta-model. T. Since 1.099 < 2.571, null hypothesis would not reject. ‡

DISCUSSION

Analysis of the factor effects

The factor effect on responses and for the all criteria's p value is shown in Table 8. A minus mark shows an antagonistic effect, while a plus mark presents a synergetic effect of the factor on the responses (Table 8) (Şimşek *et al.*, 2016).

Table 8. Factor effects and the related p values for all responses (uncodified values).

Sources	**R1 (thermal conductivity)**		**R2 (Compressive strength, 3-days)**		**R3 (Compressive strength, 28-days)**	
Term	**Effect (T)**	**P value**	**Effect (T)**	**P value**	**Effect (T)**	**P value**
PP	1.090	0.301	-2.937	**0.015***	0.875	0.402
TPE	1.315	0.218	-2.742	**0.021***	-0.079	0.939
DMT	2.952	**0.014***	-4.064	**0.002***	0.847	0.417
PP²	-1.153	0.276	1.038	0.324	-4.567	**0.001***
TPE²	-1.291	0.226	0.198	0.847	1.173	0.268
DMT²	-3.498	**0.006***	1.154	0.275	-3.634	**0.005***
PP*TPE	-0.778	0.455	1.365	0.202	-0.340	0.741
TPE*DMT	-1.245	0.242	1.912	0.085	2.299	**0.044***
PP*DMT	-0.622	0.548	3.081	**0.012***	-0.857	0.411
Sources	**R5 (slump flow)**		**R6 (production cost)**		**R7 (water permeability)**	
Term	**Effect**	**P value**	**Effect**	**P value**	**Effect**	**P value**
PP	-0.368	0.721	35,654	**0.000***	0.571	0.580
TPE	-1.143	0.280	76,101	**0.000***	-0.467	0.650
DMT	0.408	0.682	22,749	**0.000***	-1.110	0.293
PP²	-0.389	0.705	-0.000	1.000	0.161	0.876
TPE²	2.467	**0.033***	-0.000	1.000	1.360	0.204
DMT²	-3.246	**0.009***	-0.000	1.000	4.205	**0.002***
PP*TPE	-0.806	0.439	0.863	0.408	-0.112	0.913
TPE*DMT	2.417	**0.036***	0.863	0.408	-1.370	0.201
PP*DMT	0.806	0.439	0.863	0.408	-0.717	0.490

* And bold: significant at 1 % (p value); (+) synergetic effect; (-) antagonistic effect.

The response thermal conductivity is importantly influenced by the synergistic impact of linear terms belonging to DMT amount's ratio, via a p value of 0.014. The thermal conductivity is importantly influenced by the antagonistic impact of quadratic term with DMT, via a p value of 0.006; 3-day compressive strength is importantly influenced by the antagonistic impact of linear terms belonging to the ratio of PP, TPE, and DMT, via a p value of 0.015, 0.021, and 0.002, respectively. However, the interaction between the PP and TPE has a positive effect on 3-day compressive strength. 28-daycompressive strength is importantly influenced by the antagonistic impact of quadratic terms belonging to the ratio of PP and DMT, via a p value of 0.001 and 0.005, respectively. However, 28-day compressive strength is importantly influenced by the synergistic impact of interaction terms belonging to the ratio of TPE and DMT, via a p value of 0.044.Slump flow is importantly influenced by the antagonistic impact of quadratic terms belonging to the ratio of PP and DMT, via a p value of 0.033 and 0.009. However, slump flow is importantly influenced by the synergistic impact of interaction term between TPE and DMT amounts, via a p value of 0.036. These results indicate that the interaction's effect should be taken into consideration. The water permeability is importantly influenced by the antagonistic impact of quadratic term DMT, via a p value of 0.002.

Analysis of the second optimization application's effectiveness

Akçaözoğlu *et al.* (2013) used PET in concrete at the rates of 30, 40, 50, and 60%. With the addition of 60% PET, the thermal conductivity value of concrete decreased from 0.9353 W/m*K to 0.3924 W/m*K (decreased by 58%). They found that the twenty-eight-day compressive strength of the concrete, which contains PET, decreases from 43.2 MPa to 9.5 MPa (78% loss of compressive strength). Ruiz-Herrero *et al.* (2016) added 20% waste polyethylene to concrete and obtained the thermal conductivity value of concrete decreased by 55% with a 28-day compressive strength loss of 90%. Marie (2017) determined the compressive strength of the optimum concrete, which contains 20% recycled concrete aggregate and %10 rubber aggregate as 19 MPa, and its thermal conductivity value as 0.79 W/m*K.

In the validity experiment, which was done with the optimum mixing levels with the RSM based NLP, although there is a decrease of 55.2% [(60.9060.90) /(27.27-)] (please see Table 7) by the reference concrete (Table 4; M0-numbered mixture) at 28-day compressive strength, a recovery of 62.0% [(1.661.66) /(0.63-)] is obtained at thermal conductivity value. The thermal conductivity value decreases from 0.70 W/m*K to 0.63 W/m*K in the second-stage optimization study (a compressive decrease from 36.4 MPa to 27.27 MPa value occurred). Polymer-mixed concrete, which is obtained by the two-stage optimization study, is included in C 2025/ compressive strength class as it has got 28-day compressive strength at 27.27 MPa value. When it is compared to the studies in the literature, it has got the lower thermal conductivity value at the higher compressive strength. This indicates that this two-stage multi-response optimization technique is quite effective for solving polymer dosage problems.

To analyze the effectiveness of the second stage optimization application, an energy saving calculation has been made with the use of the thermal conductivity improvement ratio. The predictive heat saving for a recovery, in which a thermal conductivity can be done at the rate of

0.07 (0.700.63-) W/m*K, can be calculated in the following equations with the use of Fourier law (Ruuska *et al.*2017):

$$\text{Saving due to extra insulation: } Q = -\frac{k*A}{\Delta x} * (\Delta T) = -\frac{0.07\frac{W}{m*K}*300m^2}{0.1m} * 20K = 4200W \quad (1)$$

$$\text{Cost Saving} = (4.2\text{ kW}) * \left(\frac{0.1077\$}{\text{kWhr}}\right) = 0.452\$/\text{hr} \quad (2)$$

where

Q= Predicted heat loss from the specimen (W).

k= thermal conductivity, W/ (m*K)

ΔT= Assumed temperature difference (K).

Δx= Assumed thickness of specimen (m).

A= Assumed specimen heat transfer area (m^2).

The saving with 0.452 $/hr, which occurs in an area at 300 m2 only at 10 cm thickness, is very remarkable and these results indicate that the second optimization practice is necessary.

CONCLUSION

The results show that an experimental design, which contains interaction effects, is crucial to analyze the factors' effects effectively. For example, PP and DMT should be used together to obtain early concrete strength (second order analysis of variance for 3-day compressive strength). Moreover, PP and DMT should be used together to obtain high 28-day concrete strength and slump flow according to second order analysis of variance. DMT should also be used to obtain low thermal conductivity (in other words, thermal insulation).

The recovery rate of 57.8% in the thermal conductivity of polymer concrete composites has been obtained with a 28-day compressive strength loss of 39.57% according to reference concrete (polymers have not been used in concrete) in the first multi-response optimization application. A recovery rate of 10.0% in thermal conductivity of polymer concrete composites has been obtained with a 28-day compressive strength loss of 25.82% according to the firstly optimized concrete in this study (Figure 4).

With the rising energy prices and due to the increasing demand for energy, the efficiency in energy consumption has rapidly become a very important issue for building researchers (Huang *et al.*, 2014). The construction sector that is the largest energy consumer in the European Union countries constitutes 40% of the final energy consumption (Huang *et al.*, 2014). Looking at the energy statistics, 30% of the total energy consumption in Turkey comprises the energy consumption that arises from the residential buildings (Kazanasmaz *et al.*2014). While the efficient usage of energy in the residential sector directly reduces energy consumption, it indirectly reduces the carbon emissions from the intense heat loss in houses. Due to the high amount of energy consumption and emission values, the producers of ready-mixed concrete make great effort to take the control of energy consumption. Taking into account the selection and combination of building components, if the appropriate early design decisions are made, the building designers may contribute to the solution of energy problems.

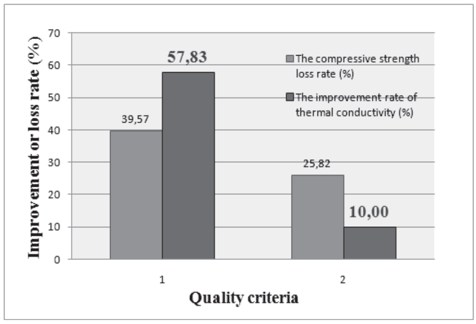


Figure 4. The 28-day compressive strength loss and the recovery rate of thermal conductivity. (1) These rates, which are obtained by TOPSIS based Taguchi optimization, are also called the first optimization according to the reference concrete M0 (Şimşek and Uygunoğlu, 2016); these rates, which are obtained by RSM based NLP optimization, are also called second optimization in this study according to the first optimized concrete.

The illustrative example, which was calculated by 10.0 % recovery rates in thermal conductivity, shows that the saving with 0.452 $/hr, which occurs in an area at 300m2 only at 10cm thickness, is very remarkable and these results indicate that the second optimization practice is necessary. Furthermore, it is possible to get a low thermal conductivity value at the higher compressive strength (Figure 5).

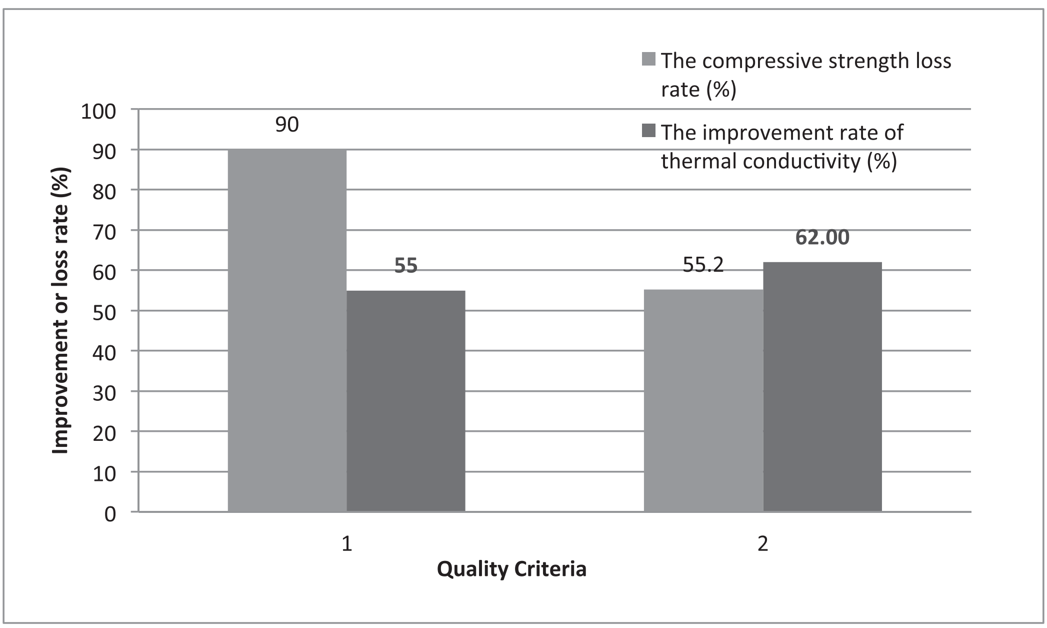


Figure 5. These rates have been calculated in Ruiz-Herrero *et al.*'s (2016) study (1); these rates, which are obtained by RSM based NLP optimization, are also called second optimization in this study (2).

The two-step multi-response optimization based design of experiments should be used to determine optimal mix design in terms of reducing the number of experiments, to avoid of time, energy, and materials consumption.

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