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Multi-response optimization of polymer blended concrete: A TOPSIS based Taguchi application

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HIGHLIGHTS

- In order to determine optimal mixture proportions of polymer blended concrete, a TOPSIS based Taguchi optimization was applied.
- Reaching the desired level of heat insulation on an acceptable level of compressive strength was achieved with the multi-response optimization methods.
- Polymer concrete having a lower thermal conductivity of 57.8% according to reference concrete was achieved with a 28th compressive strength loss of only 40.2 via optimization methods.
- Polypropylene was found more attractive option with regards to environmental problem.

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ABSTRACT

Using polymeric materials in the concrete mix may increase the heat insulation of the concrete, but it also causes a decrease in the compressive strength of the concrete. Reaching the desired level of heat insulation on an acceptable level of compressive strength has been achieved with the multi-response optimization methods. With this purpose, TOPSIS based Taguchi method has been used to determine optimal mixture proportions of concrete contains polymers such as high density polyethylene, low density polyethylene, polypropylene, thermoplastic elastomer, dimethyl terephthalate, polyethylene terephthalate, polyethylene naphthalate. Polymer blended concrete having a lower thermal conductivity of 57.8% according to reference concrete has been achieved with a 28-day compressive strength loss of 40.2%. Produced polymer blended concrete has a thermal conductivity of 0.70 W/m K and 28-day compressive strength of 36.8 MPa. Furthermore, polypropylene has been found more attractive option with regards to environmental problem. This study provides to eliminate the polymeric materials that cause an environmental problem and ensure energy saving to manufacturer.

1. Introduction

In recent years, many researchers have made a study on the area with an idea that polymeric materials would have specific effects on concrete. Polymeric materials contain wastes such as rubber type and polyethylene terephthalate (PET) have quickly become very big environmental problem [1]. Mounanga et al. [2] determined that the thermal conductivity value of the lightweight concrete produced with polyurethane foam wastes as 0.34 W/m K, and they also found out that the mechanical strength varied between 1.3 MPa and 10.4 MPa. Yesilata et al. [3] used the waste PET and rubber pieces in order to increase the thermal resistivity of concrete. They achieved an 18.52% increase in the thermal conductivity value with the addition of rubber pieces, and 18.16% increase in the thermal conductivity value with the addition of PET pieces. Demirboga and Kan [4] used the expanded polystyrene in the ready-mixed concrete instead of fine aggregate, at the rates of 25, 50, 75 and 100%, respectively. They found out that the polystyrene aggregates decreased the thermal conductivity of the reference concrete at 70%. Akcaozlu et al. [5] used PET in concrete at the rates of 30, 40, 50 and 60%. As an additional to 60% PET, thermal conductivity value of concrete decreased 0.9353 W/m K–0.3924 W/m K. They found out that twenty-eight day compressive strength of the concrete which contained PET, decreased from 43.2 MPa to 9.5 MPa. Chen et al. [6] determined the compressive strength of the optimum lightweight concrete

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containing polystyrene as 13 MPa, and its thermal conductivity value as 0.25 W/m K. Youssf et al. [7] investigated the compressive strength of the waste rubbers and the concrete containing cylindrical polymer tubes. When they used rubber particles instead of fine aggregate at 9.5%, they observed a 37% pressure drop. Lv et al. [8] found out that the compressive strength decreased from 41.5 MPa to 7 MPa, the splitting tensile strength decreased from 4.38 MPa to 0.79 MPa and the flexural strength decreased from 4.68 MPa to 0.87 MPa when they used rubber particles instead of fine aggregate at 100%.

When all these studies have been considered; it has been observed that a decrease occurs on mechanical features while polymeric substances recover thermal conductivity of concrete. Because different materials which are added into concrete mixture may have positive and negative effects on concrete's thermal, mechanical and workability features. Recovering only one feature of concrete without considering other features restricts pretty industrial applications of the product. For example, use of polymeric wastes in concrete mixtures may increase heat insulation on concrete but at the same time it causes decrease on compressive strength of concrete. All criteria require to be simultaneously optimized in the event that products are to find application area in industry. Thus it will be possible that it can obtain desired heat-insulation level on compressive strength on acceptable level.

In order to get desired quality on concrete, finding optimal mix ratio of ready concrete mixture is quite important issue on material and design engineering [9–11]. Many optimization and modeling methods based on experimental design have been suggested as many of them are one response optimization on researching optimum mixture parameters for different concrete types on literature. Especially on these studies, response surface methodology has been used in normal-weight concrete [12–14], alkali-activate concrete [15], slight aggregate concrete [16,17], concrete involving fly-ash aggregate [18], steel fiber-reinforced concrete [19–21], concrete involving waste paper [22] and metakaolin-reinforced concrete [23]; Taguchi method has also been used for self-consolidating concrete [9,24,25], slight concrete involving silica fume [26,27,28], geopolymer concrete [28], high strength concrete [29], pavement concrete [30], concrete involving cinder [31], methyl methacrylate-reinforced concrete [32], slight concrete involving fly-ash [33], concrete involving marble powder [34], concrete involving volcanic tuff [35]. Partial factorial design has also been used in self-consolidating concrete [36], concrete involving regained aggregate [37] and fiber-reinforced concrete [38]. A few of these studies involving experimental design include multi-response optimization. TOPSIS (Technique of Ordering Preferences by Similarity to Ideal Solutions) method [39–42] which is commonly used on different areas is preferred as it does not involve complex mathematical processes against grey relational calculus and VIKOR (Vlse Kriterijumska Optimizacija I Kompromisno Resenje) [9]. The TOPSIS-based Taguchi optimization is easy to apply compared to the other multi-response optimization methods such as the Grey Relational calculus and VIKOR based Taguchi method [9]. The application of the TOPSIS-based Taguchi method does not require complicated calculation with non-linear object and constraint functions. Moreover, multi-response optimization methodology using TOPSIS based Taguchi application can be easily performed with Microsoft Excel® sheet. An orthogonal array is used to reduce the testing time and the experimental costs and TOPSIS can be easily adapted and performed with orthogonal arrays. The implementation of the TOPSIS can easily be extended to include more than two responses. This method has been preferred on account of these properties. The authors are not aware of any literature that discusses the multi-response polymer dosage optimization problem by using the TOPSIS-based Taguchi method.

This study suggests on a multi-response optimization methodology for the determination of polymer blended concrete's (PBC) which contains high density polyethylene (HDPE), low density polyethylene (LDPE), polypropylene (PP), thermoplastic elastomer (TPE), dimethyl terephthalate (DMT), polyethylene terephthalate (PET), polyethylene naphthalate (PEN) optimal mixture ratio. Main contribution of the study is that PBC's thermal, mechanical and workability features are optimized as simultaneously via TOPSIS based Taguchi method. For reaching the desired level of heat insulation on an acceptable level of compressive strength on PBC, a multi-response optimization methods such as TOPSIS based Taguchi design was applied. Thus, it is aimed on the one hand that the polymeric materials that constitute an environmental problem and that are hard to disappear in the nature, as also ensuring energy saving. High purity polymeric materials which have homogeneous properties were preferred on the study in order to results use in industry. Polymeric materials and high amount waste that may occur in the future has been selected in this study. Thus it has been aimed that polymeric materials which are an environmental problem are removed, using ready mixed concrete which is most-used building material. Because regaining polymeric materials by thermal processes such as pyrolysis is a great environmental problem as it causes greenhouse gas and carbon emission.

Another contribution of this work is that production cost of PBC has added between quality criteria. Production cost of PBC has not been considered in previous studies. This PBC is divided in two points from the conventional concrete. First of all, it contains recycled materials such as HDPE, LDPE, PP and PET. In this regard, it is important for the environment according to the disposal of these materials. Secondly, the PBC has low thermal conductivity compared to the conventional concrete. This property of the PBC has made its use more attractive throughout the world.

First of all, factors and their levels effect on thermal, workability and mechanical properties of polymer concrete have been defined. Then, the experiments have been carried out according to runs determined by orthogonal arrays and the results which have been obtained. A decision matrix is thereafter created with the signal to noise (S/N) ratios calculated by experimental data, and the TOPSIS method is utilized to convert the multi-response problem into a one-response problem [9].

2. Materials

CEM I 42.5 R type cement has a specific gravity of 3.09 and Blaine fineness of 3540 cm^2/g has been used in this study. Chemical oxide composition of the binder materials has been given in Table 1. A polycarboxylate ether based super plasticizer (SP) has been used in all concrete mixtures and physical properties of SP have been given in Table 2 [9]. Fine aggregate with a size of smaller than 4 mm and coarse aggregate (I) with a size between 4 mm and 11.2 mm and coarse aggregate (II) with a size between 11.2 mm and 22.4 mm have been used in concrete mixtures. The fine and coarse aggregates has specific gravities of 2.66 and 2.71 and mean water absorptions of 1.55% and 0.91%, respectively.

Table 1
Chemical oxide composition of cement and fly ash.

Chemical analysis	Cement (%)	Fly ash (%)
CaO	66.12	4.81
SiO_2	21.72	56.16
Al_2O_3	5.94	23.3
Fe_2O_3	2.59	6.31
SO_3	1.61	0.75
MgO	1.19	2.09
K_2O	0.64	2.49
Na_2O	0.13	0.31
Cl	0.0076	0.0019
Loss of ignition	3.69	2.22

Table 2
Features of the SP at 20 °C.

Properties	Super plasticizer
Chemical description	Polycarboxylic type polymer
Color	Light brown
Specific gravity (kg/L)	1.06–1.10
Chlorine content % (EN 480-10)	<0.1
Alkaline content% (EN 480-12)	<3
State	Liquid

Polymeric materials such as HDPE, LDPE, PP and PET used to reduce thermal conductivity of concrete were supplied from recycling facilities as granules. Polymeric materials such as TPE, DMT and PEN have been supplied from polyester industry. Their properties have been given in Table 3.

3. Offered multi-response optimization methodology

There are 8 flow steps in the determination of the optimal mix proportions of the PBC (Fig. 1).

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, production cost, water permeability of hardened concrete have been determined as polymer concrete quality criteria. Optimal mixture levels of high density polyethylene, low density polyethylene, polypropylene, thermoplastic elastomer, dimethyl terephthalate, polyethylene terephthalate, polyethylene naphthalate, amount of cement and fly ash, water to binder ratio, the percentage of super plasticizer content, fine aggregate amount to total aggregate amount ratio and coarse aggregate amount to total aggregate amount ratio (4–16 mm) have been determined using TOPSIS based Taguchi method. The TOPSIS process is used to combine all identified performance values of the system into a single value that can then be used as a single performance in the multi-response optimization issues [9].

The ideal point method is a method that alternatives are ordered as deviating from ideal point. The Ideal point is a decision result which is mostly intended and advantageous one. Most similar alternative to ideal point is best alternative. Deviations from the ideal point are measured by measuring range [9,43–45]. Number of criteria which requires to be considered on decision process is too many usually. While some criteria value are intended to be made maximum on decision which will be taken in consideration of these criteria, some values are intended to be decreased as possible. Some criteria values that we intend on acquired alternative results can be minimized but if it is high on intended criteria to be minimized, it is not an ideal solution. It is not easy to compare such an alternative with other alternatives about supremacy or its weakness. With the purpose of balancing these values, similar methods to the ideal solution that we have mentioned are used. The methods such as TOPSIS method order alternatives and make their selections easy in terms of ideal solution similarity. After alternatives on decision process are designated, it provides supremacy to select TOPSIS method against other ideal solutions that criteria values are made normal and criteria which is made normal on this matrix is weighted with the purpose of obtaining a standard measurement [9,43–45].

4. Identifying performance optimization provisions of PBC

4.1. PBC's optimization objectives

Determination of the optimal mixture parameters is an important issue to obtain concrete with the desired properties [11]. Reaching the desired level of heat insulation on an acceptable level of compressive strength will be tried to achieve with the optimization methods. Thus, it is aimed on the one hand that the disposal of polymeric materials that constitute an environmental problem, as they also ensure energy saving by the multi-response optimization methods. Therefore, this study provides polymers' performance evaluation in concrete to the polymer materials manufacturer.

While using the energy efficiently 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 control of energy consumption. Taking into account of the selection and combination of building components, if appropriate early design decisions are made, the building designers may contribute the solution of energy problems. In order to reach the intended thermal conductivity values at a reasonable value of compressive strength, simultaneous and multi-responsive optimization techniques that have never been performed before in the studies of thermal conductance coefficient in PBC will be used.

4.2. PBC performance criteria

First quality criterion is thermal conductivity value which informs about thermal insulation of PBC and which is one of most important thermal features. Concrete type which has got low thermal conductivity value is concrete type that there is little heat loss and thermal damage [9,25]. TCI- Thermal Conductivity Analyzer model which is used in study can be determining the thermal conductivity of three different group's material varieties as foam, polymer and ceramic in a constant of room temperature. The device can determine the thermal conductivity of by a precision sensor which has got 30 mm diameter. Heat conductivity coefficients of concrete involving polymeric waste have been determined by hot wire method which is given on ASTM C 1113 standards [46]. This method is a measurement method which is

Table 3
Properties of the polymers used in study.

Properties	Values						
	LDPE	HDPE	PP	TPE	PEN	DMT	PET
Melting flow rate, g/10dk	2.0–3.5	4.5–6.0	8.0	12–20	–	–	–
Density, g/cm^3	0.918-0.922	0.963-0.967	0.905	1.20	1.35	1.2	1.38
Melting point, °C	110	95	230–260	205–215	155	142	235
Tensile strength at yield, kg/cm^2	85	300	280	300	200	–	80
Tensile strength at break, kg/cm^2	140	170	–	–	–	–	–
Elongation at break, %	600	1250	6	–	–	–	–
Hardness (Shore D)	44	–	91	–	–	–	–
Flexing endurance, MPa	–	1100	–	500	5000	–	2000
Glass transition temperature, °C	80–90	–	–	–	–	–	–
Water absorption, %	–	–	–	0.7	0.4	–	0.1–0.7
Granule spacing, mm	<4 mm	<4 mm	<4 mm	<4 mm	<4 mm	<4 mm	<4 mm

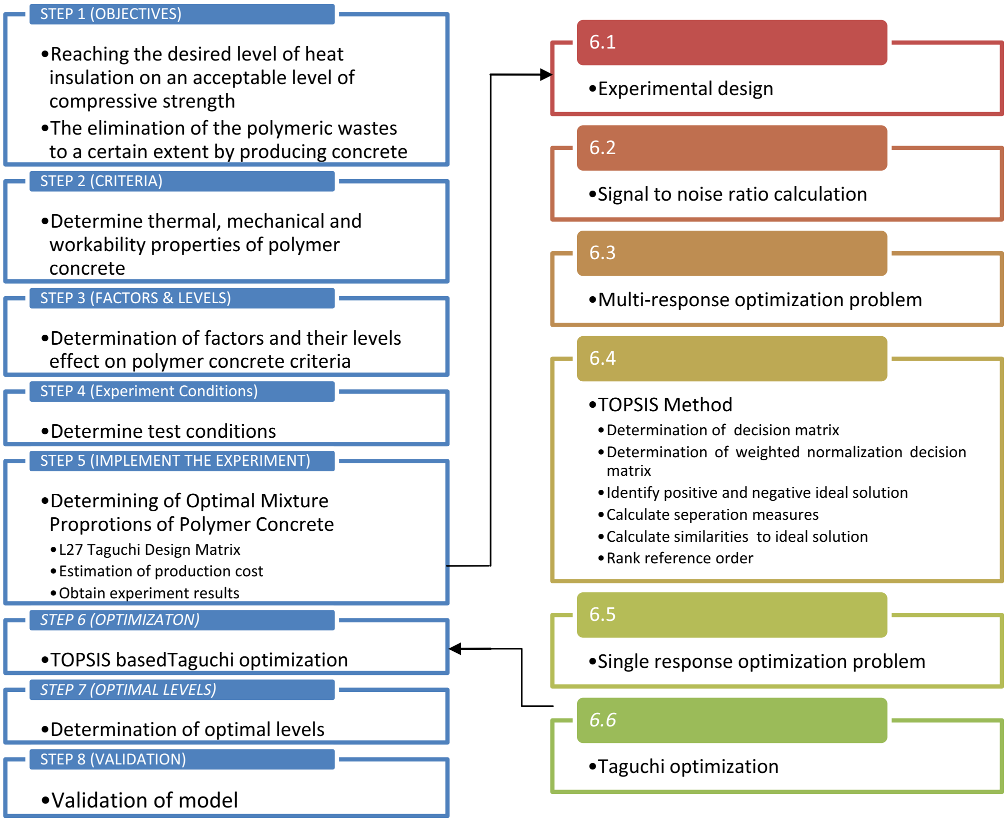

Fig. 1. Offered performance optimization framework of polymer concrete [8].

commonly used for such materials which have got full volume such as concrete and brick.

For each PBC mix, the compressive strength of three 150 mm cubes has been determined for 3, 7, 28 days according to the EN 12390/3 [47]. Splitting tensile strength tests are performed on three 150 mm cube samples for 28 days according to the EN 12390/6 [9,48,49]. Higher compressive and higher split tensile strength means a better mechanical endurance [9,25].

Workability of fresh polymer concrete has been determined using Abrams slump cone method according to EN 12350-2 [9,50]. Slump of fresh PBC which needs to be maximized gives information to user concrete workability. Determination of the percentage of water absorption of hardened PBC has been conducted on 150 × 150 × 150 mm cubic samples cured in water for twenty-eight day according to EN 12390-7 [51]. It is demanded that the percentage of water absorption of hardened PBC should be minimized in terms of PBC quality [9,25]. The other criterion is that the production cost is required to be the minimized one. The water permeability test has been carried out on 150 × 150 × 150 mm cubic samples in accordance with procedures specified in EN 12390-8 [9,52,53]. The samples have been placed in test device and 500 ± 50 kPa water pressures has been applied during 72 ± 2 h [52]. During the test, pressure untreated surface of the specimen has been observed at regular intervals and the situation observed in surface water has been recorded. If it is found in water leakage, it is concluded that the experiment resulted [52]. In order to determine on the height of water pass in samples, the specimen has been divided into two parts to be parallel to be direction of water flow. Measurements have been made on to divided parts per cm using digital compass and arithmetic mean of these measurements has been evaluated (Fig. 2) [25].

Nine performance criteria are identified for the polymer concrete. The first performance criterion is defined as the thermal conductivity which provides information on energy savings. The second, third and fourth performance criteria are identified respectively as the percentages of 3-day, 7-day and 28-day compressive

Fig. 2. Water penetration test on PCB samples.

Table 4
Normalized weights of quality criteria.

Quality criteria	Exemplar	Definition	Type of concrete test	Desired properties	Weights[a]	Normalized weights
1	R1	Thermal conductivity (W/m K)	Hardened concrete test	Smaller is better	10	0.192
2	R2	Compressive strength (N/mm^2) 3rd day	Hardened concrete test	Higher is better	7	0.135
3	R3	Compressive strength (N/mm^2) 7th day	Hardened concrete test	Higher is better	6	0.115
4	R4	Compressive strength (N/mm^2) 28th day	Hardened concrete test	Higher is better	10	0.192
5	R5	Slump flow (cm)	Fresh concrete test	Higher is better	6	0.115
6	R6	Water absorption (%)	Hardened concrete test	Smaller is better	5	0.096
7	R7	Splitting tensile strength (N/mm^2) 28 days	Hardened concrete test	Higher is better	4	0.077
8	R8	Production cost ($/mm^2)	Hardened concrete test	Smaller is better	2	0.038
9	R9	Water permeability (cm)	Hardened concrete test	Smaller is better	2	0.038
		Total			52	1.000

[a] The weights of responses are determined by three laboratory expert.

strength. Fifth criterion is slump flow value gives higher concrete workability [9]. The other performance criteria of PBC is identified respectively as the percentage of the water absorption, 28-day splitting tensile strength gives information about durability, the water permeability and production cost. The designated weight for nine performance criteria has been presented in Table 4.

4.3. Definition of factors and experiment conditions

Thirteen factors that each has three control levels affect the PBC identified quality. The percentage of high density polyethylene, low density polyethylene, polypropylene, thermoplastic elastomer, dimethyl terephthalate, polyethylene terephthalate, polyethylene naphthalate have been instead for the fine aggregate. The other factors are defined as cement dosage, fly ash amount, water to binder ratio, super-plasticizer content, fine aggregate amount to total aggregate ratio and coarse aggregate number (I) to total aggregate ratio. These factors are symbolized X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}, X_{11}, X_{12} and X_{13} respectively (Table 5).

5. Determining of optimal mix parameters of PBC

5.1. Selecting of orthogonal experiment matrix

L_{27} (3^{13}) orthogonal array is used to perform the experiments and thirteen factors can be evaluated in twenty-seven experiments. L_{27} orthogonal array has been chosen to analyze and optimize all of the polymeric materials simultaneously. Uncoded and coded values of factors' level are given in Table 6 with experimental runs.

Table 5
Factors and their levels.

Factors	Definition	Bounds		
		First bound	Second bound	Third bound
X_1	High density polyethylene (%)	1	5	10
X_2	Low density polyethylene (%)	1	5	10
X_3	Polypropylene (%)	1	5	10
X_4	Thermoplastic elastomer (%)	1	5	10
X_5	Dimethyl terephthalate (%)	1	5	10
X_6	Polyethylene terephthalate (%)	1	5	10
X_7	Polyethylene naphthalate (%)	1	5	10
X_8	Cement dosage (kg)	350	400	450
X_9	Fly ash content (kg)	80	100	120
X_{10}	Water to binder ratio	0.38	0.42	0.46
X_{11}	Super plasticizer content (%)[a]	0.80	1.05	1.30
X_{12}	Fine aggregate to total aggregate ratio	0.40	0.50	0.60
X_{13}	Coarse aggregate (I) to total aggregate ratio	0.15	0.20	0.25

[a] Defined for one hundred kilograms binder (cement and ash).

5.2. Production cost of PBC

The purchase price of HDPE, LDPE, PP, TPE, DMT, PET and PEN, cement, fly ash, water, super-plasticizer, and fine aggregate and coarse aggregate materials were given in Table 6. The production costs for all experiment runs are calculated by using the data in Table 6 and given in Table 7.

5.3. TOPSIS based Taguchi optimization

A Taguchi orthogonal array [9] (L_{27}) has been chosen to register the experiment results in this study. Experimental results obtained by L_{27} Taguchi design have been given in Table 7. This model ensures the nine performance criteria simultaneously for overcoming the multi-response-optimization problem (in Table 8) [9]. The S/N ratios for the lower-the-better and the-higher-the-better responses are calculated by using Eqs. (1) and (2) respectively for each response. The experimental design and the S/N ratios are given in Table 8, columns 2–10 [9].

$$\eta_{ij} = -10\log_{10}\left[\frac{1}{n}\sum_{k=1}^{n} y_{ijk}^2\right] \quad (1)$$

$$\eta_{ij} = -10\log_{10}\left[\frac{1}{n}\sum_{ki=1}^{n} \frac{1}{y_{ijk}^2}\right] \quad (2)$$

In the Eqs. (1) and (2); η_{ij} is the S/N ratio for the response j of experimental number i, and y_{ijk} is the experiment result for the response j of the experiment i, in the k th replication; n is the total number of replications [54–57].

Table 6
Individual cost for all materials.

Materials	Purchasing cost ($/kg)
HDPE	2.526
LDPE	2.526
PP	2.301
TPE	4.845
DMT	1.490
PET	2.025
PEN	10.71
Cement	0.07
Fly ash	0.03
Water	0.003
Super-plasticizer	2.0
Fine aggregate (<4 mm)	0.05
Coarse aggregate (>4 mm)	0.045

Table 7
L_{27} experimental design and results.

Exp. no.	Wet [a]U.W. (g)	Dry [a]U.W. (g)	R1 (W/m K)	R2 (N/mm^2)	R3 (N/mm^2)	R4 (N/mm^2)	R5 (cm)	R6 (%)	R7 (N/mm^2)	R8 (TL)	R9 (cm)
M0	8164	7999	1.66	44.40	50.40	60.90	16	2.02	4.00	119.70	0.70
MT1	7950	7850	1.30	26.70	36.10	41.30	2	1.26	2.67	191.50	2.12
MT2	7720	7606	1.20	30.60	38.20	46.10	44	1.48	2.40	375.99	3.63
MT3	8019	7903	1.12	25.00	28.00	40.60	80	1.45	2.54	627.70	8.56
MT4	7724	7439	1.15	30.04	34.60	46.30	22	3.69	2.15	359.54	1.22
MT5	7470	7164	0.71	9.91	16.33	26.20	80	4.10	2.33	378.47	1.24
MT6	7427	7157	0.82	21.87	27.24	32.30	5	3.64	2.14	766.88	1.72
MT7	7358	7066	0.83	18.10	37.18	37.70	80	3.97	2.58	422.52	2.47
MT8	7163	6851	0.94	20.10	22.83	28.30	8	4.36	1.95	809.54	2.68
MT9	7280	6967	0.86	24.90	29.40	34.20	15	4.30	2.05	706.19	4.97
MT10	7617	7484	1.30	27.10	34.90	42.80	19	1.75	2.45	731.75	3.54
MT11	7490	7338	1.26	30.90	38.40	42.80	16	2.03	2.65	536.96	2.64
MT12	7741	7561	1.20	34.50	46.20	50.90	20	2.33	2.80	462.45	2.12
MT13	7723	7543	1.30	28.70	36.60	53.90	17	2.33	2.35	547.78	0.94
MT14	7543	7264	1.15	27.50	41.60	47.90	19	3.70	2.20	379.85	1.58
MT15	7301	7150	1.08	18.70	28.80	35.40	22	2.07	2.35	583.19	2.25
MT16	7523	7198	1.40	36.10	40.40	40.60	70	4.32	3.60	766.80	2.64
MT17	7669	7328	1.43	37.10	45.50	48.10	70	4.45	2.50	374.83	3.15
MT18	7866	7645	1.33	33.95	41.90	49.40	80	2.81	3.40	533.27	0.83
MT19	7317	7002	1.45	30.80	31.00	37.50	14	4.31	2.90	687.60	5.27
MT20	7708	7394	1.33	37.30	37.30	48.60	70	4.07	3.60	582.48	4.98
MT21	7521	7173	1.20	37.50	35.80	47.30	19	4.63	3.47	446.78	0.33
MT22	7666	7343	1.16	33.80	39.40	49.00	20	4.21	3.40	614.37	2.92
MT23	7291	6952	1.34	27.70	30.60	37.11	14	4.65	3.10	853.56	3.58
MT24	7426	7086	1.21	27.60	32.10	48.00	14	4.58	3.70	430.77	3.14
MT25	7498	7196	1.41	32.90	38.40	43.73	17	4.03	3.80	456.24	2.74
MT26	7473	7164	1.35	28.40	30.00	36.00	17	4.13	2.70	704.40	6.57
MT27	7350	6986	1.29	26.90	32.50	35.30	16	4.95	3.00	480.67	6.32

[a] U.W: unit weight.

In Table 8, columns 2–10 are exemplified as the decision matrix for the initial step of the TOPSIS method which converts the multi-response optimization problem into a single response problem [9]. A sample calculation for the weighted normalized matrix is showed in Table 8. The positive ideal solution, A^* (A_i^*; $i = 1,2,\ldots, m$), is made of all the best values (maximum S/N ratio) and the negative-ideal solution, A^- (A_i^-; $i = 1,2,\ldots,m$), is made of all the worst values (minimum S/N ratio) at the responses in the weighted normalized decision matrix. (Si^*) symbolizes the distance of an alternative (experimental number) i to the positive ideal solution and (Si^-) symbolizes the distance from the negative ideal solution [9]. In each scenario; calculation of the similarity of the ideal solutions, (C_i^*: deputy response) also seen in same Table [9]. The recent results are illustrated in Table 8, last column.

The normalization methods led to the final parameter design of $(X_2)_1$, $(X_2)_2$, $(X_3)_3$, $(X_4)_3$, $(X_5)_3$, $(X_6)_2$, $(X_7)_2$, $(X_8)_3$, $(X_9)_3$, $(X_{10})_3$, $(X_{11})_2$, $(X_{12})_2$, $(X_{13})_1$ (Fig. 3).

In order to determine on improvement ratio of PBC's properties, an experiment has been carried out using the optimum factor levels. Experiment results for PBC's properties and reference sample does not contain polymer method are given in Table 9.

6. Results and discussions

6.1. Optimization validation

With a 40.8% decrease in 28-day compressive strength, 57.8% improvements in thermal conductivity has been achieved using TOPSIS based Taguchi optimization (Table 9). The slump flow value has been almost found the same as the reference concrete.

As shown in main effect plot for thermal conductivity, the thermal conductivity of PBC has decreased with increasing amount of dimethyl terephthalate, thermoplastic elastomer and polypropylene materials (Fig. 4a). The thermal conductivity of PBC has not been changed significantly with increasing amount of Polyethylene terephthalate and polyethylene naphthalate (for factor levels which alter from 1 to 10%). It was found that high density polyethylene has negative effect on concrete thermal conductivity. A relatively low thermal conductivity values have been obtained at 5% factor level (Fig. 4a).

When analyzed main effect plot for compressive strength, it has been concluded that the 3-day, 7-day and 28-day compressive strength of PBC decreased with increasing amount of polymer materials (Fig. 4b–d). However, it can be said that the early strength of PBC has been increased significantly with increasing amount of high density polyethylene (Fig. 4b). Moreover, the 7-day and 28-day compressive strength of PBC have not been changed significantly with the increasing amount of and polyethylene naphthalate (for factor levels which alter from 1 to 10%) (Fig. 4c–d).

It can be interpreted in main effect plot for slump flow that the slump flow of PBC has decreased with increasing amount of high density polyethylene, polypropylene, thermoplastic elastomer and polyethylene terephthalate (Fig. 4e). The slump flow of PBC has not been changed significantly with the increasing amount of dimethyl terephthalate and polyethylene naphthalate (for factor levels which alter from 1 to 10%) (Fig. 4e). The slump flow of PBC only has increased with the increasing amount of low density polyethylene.

The water absorption of PBC has increased with the increasing amount of high density polyethylene, low density polyethylene, polypropylene, thermoplastic elastomer and has not been changed significantly with increasing amount of dimethyl terephthalate and polyethylene naphthalate and polyethylene terephthalate (for factor levels which alter from 1 to 10%) (Fig. 4f). The 28-day splitting tensile strength of PBC has decreased with the increasing amount of polymeric materials except high density polyethylene (Fig. 4g). The water permeability of polymer concrete has decreased with increasing amount of polypropylene only.

Table 8
S/N ratios calculated by Minitab®, and TOPSIS method implementation.

	Decision matrix (S/N ratios)									Weighted normalized decision matrix									S_i^*	S_i^-	C_i^*
Response	R1	R2	R3	R4	R5	R6	R7	R8	R9	v_{i1}	v_{i2}	v_{i3}	v_{i4}	v_{i5}	v_{i6}	v_{i7}	v_{i8}	v_{i9}			
Weight	0.192[b]	0.135	0.115	0.192	0.115	0.096	0.077	0.038	0.038												
1	−2.279[b]	28.530	31.150	32.319	6.021	−2.007	8.530	−45.64	−6.53	−0.04[b]	0.026	0.023	0.037	0.005	−0.003	0.014	−0.006	−0.005	0.096[c]	0.030[d]	0.237[e]
2	−1.584	29.714	31.641	33.274	32.869	−3.405	7.604	−51.50	−11.21	−0.03	0.027	0.023	0.038	0.026	−0.006	0.013	−0.007	−0.008	0.082	0.042	0.340
3	−0.984	27.959	28.943	32.171	38.062	−3.227	8.097	−55.6	−18.65	−0.02	0.025	0.021	0.037	0.030	−0.006	0.014	−0.008	−0.014	0.073	0.051	0.412
4	−1.214	29.554	30.782	33.312	26.848	−11.34	6.649	−51.11	−1.73	−0.02	0.027	0.022	0.038	0.021	−0.019	0.011	−0.007	−0.001	0.077	0.043	0.358
5	2.975	19.921	24.260	28.366	38.062	−12.26	7.347	−51.56	−1.87	0.05	0.018	0.018	0.032	0.030	−0.021	0.012	−0.007	−0.001	0.025	0.112	0.817
6	1.724	26.797	28.704	30.184	13.979	−11.22	6.608	−57.69	−4.69	0.03	0.024	0.021	0.035	0.011	−0.019	0.011	−0.008	−0.003	0.037	0.088	0.706
7	1.618	25.154	31.406	31.527	38.062	−11.98	8.232	−52.52	−7.84	0.03	0.023	0.023	0.036	0.030	−0.021	0.014	−0.007	−0.006	0.033	0.090	0.730
8	0.537	26.064	27.170	29.036	18.062	−12.79	5.801	−58.16	−8.57	0.01	0.023	0.020	0.033	0.014	−0.022	0.010	−0.008	−0.006	0.053	0.067	0.561
9	1.310	27.924	29.367	30.681	23.522	−12.67	6.235	−56.98	−13.93	0.02	0.025	0.021	0.035	0.019	−0.022	0.010	−0.008	−0.010	0.042	0.081	0.661
10	−2.279	28.659	30.857	32.629	25.575	−4.861	7.783	−57.29	−10.98	−0.04	0.026	0.022	0.037	0.020	−0.008	0.013	−0.008	−0.008	0.094	0.030	0.242
11	−2.007	29.799	31.687	32.629	24.082	−6.150	8.465	−54.60	−8.43	−0.03	0.027	0.023	0.037	0.019	−0.011	0.014	−0.007	−0.006	0.090	0.032	0.265
12	−1.584	30.756	33.293	34.134	26.021	−7.347	8.943	−53.30	−6.51	−0.03	0.028	0.024	0.039	0.021	−0.013	0.015	−0.007	−0.005	0.082	0.039	0.320
13	−2.279	29.158	31.270	34.632	24.609	−7.347	7.421	−54.77	0.55	−0.04	0.026	0.023	0.040	0.019	−0.013	0.012	−0.007	0.000	0.094	0.031	0.249
14	−1.214	28.787	32.382	33.607	25.575	−11.36	6.848	−51.59	−3.99	−0.02	0.026	0.023	0.038	0.020	−0.020	0.011	−0.007	−0.003	0.077	0.042	0.353
15	−0.668	25.437	29.188	30.980	26.848	−6.319	7.421	−55.32	−7.04	−0.01	0.023	0.021	0.035	0.021	−0.011	0.012	−0.008	−0.005	0.067	0.051	0.432
16	−2.923	31.150	32.128	32.171	36.902	−12.71	11.126	−57.70	−8.44	−0.05	0.028	0.023	0.037	0.029	−0.022	0.019	−0.008	−0.006	0.106	0.030	0.222
17	−3.107	31.387	33.160	33.643	36.902	−12.97	7.959	−51.48	−9.97	−0.05	0.028	0.024	0.039	0.029	−0.022	0.013	−0.007	−0.007	0.109	0.029	0.209
18	−2.477	30.617	32.444	33.875	38.062	−8.974	10.630	−54.54	1.58	−0.04	0.027	0.024	0.039	0.030	−0.015	0.018	−0.007	0.001	0.097	0.037	0.275
19	−3.227	29.771	29.827	31.481	22.923	−12.69	9.248	−56.75	−14.44	−0.06	0.027	0.022	0.036	0.018	−0.022	0.015	−0.008	−0.011	0.113	0.018	0.139
20	−2.477	31.434	31.434	33.733	36.902	−12.19	11.126	−55.31	−13.95	−0.04	0.028	0.023	0.039	0.029	−0.021	0.019	−0.008	−0.010	0.099	0.032	0.246
21	−1.584	31.481	31.078	33.497	25.575	−13.31	10.807	−53.00	9.54	−0.03	0.028	0.023	0.038	0.020	−0.023	0.018	−0.007	0.007	0.083	0.042	0.334
22	−1.289	30.578	31.910	33.804	26.021	−12.49	10.630	−55.77	−9.31	−0.02	0.027	0.023	0.039	0.021	−0.021	0.018	−0.008	−0.007	0.079	0.041	0.343
23	−2.542	28.850	29.714	31.390	22.923	−13.35	9.827	−58.62	−11.09	−0.05	0.026	0.022	0.036	0.018	−0.023	0.016	−0.008	−0.008	0.101	0.022	0.180
24	−1.656	28.818	30.130	33.625	22.923	−13.22	11.364	−52.68	−9.94	−0.03	0.026	0.022	0.039	0.018	−0.023	0.019	−0.007	−0.007	0.086	0.034	0.287
25	−2.984	30.344	31.687	32.816	24.609	−12.11	11.596	−53.18	−8.75	−0.05	0.027	0.023	0.038	0.019	−0.021	0.019	−0.007	−0.006	0.107	0.023	0.177
26	−2.607	29.066	29.542	31.126	24.609	−12.32	8.627	−56.96	−16.35	−0.05	0.026	0.021	0.036	0.019	−0.021	0.014	−0.008	−0.012	0.102	0.021	0.173
27	−2.212	28.595	30.238	30.955	24.082	−13.89	9.542	−53.64	−16.02	−0.04	0.026	0.022	0.035	0.019	−0.024	0.016	−0.007	−0.012	0.096	0.026	0.210
	10.97 [a]	149.9	159.1	167.9	146.2	56.0	46.0	282.8	52.4	$A^* =$ 0.052	0.029	0.024	0.040	0.030	−0.003	0.019	−0.006	−0.007			
										$A^- =$ −0.057	0.018	0.018	0.032	0.005	−0.024	0.010	−0.008	−0.014			

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[a] The square root of sum of squares of each element in the columns.

[b] From [9]: $0.192 * [(-2.28)/(10.97)] = -0.04$.

[c] From [9]: $\{[(-0.04) - (0.052)]^2 + \ldots\ldots + [(-0.005) - (-0.007)]^2\}^{1/2} = 0.096$.

[d] From [9]: $\{[(-0.04) - (-0.057)]^2 \ldots\ldots + [(-0.005) - (-0.014)]^2\}^{1/2} = 0.030$.

[e] From [9]: $0.030/(0.030 + 0.096) = 0.237$.

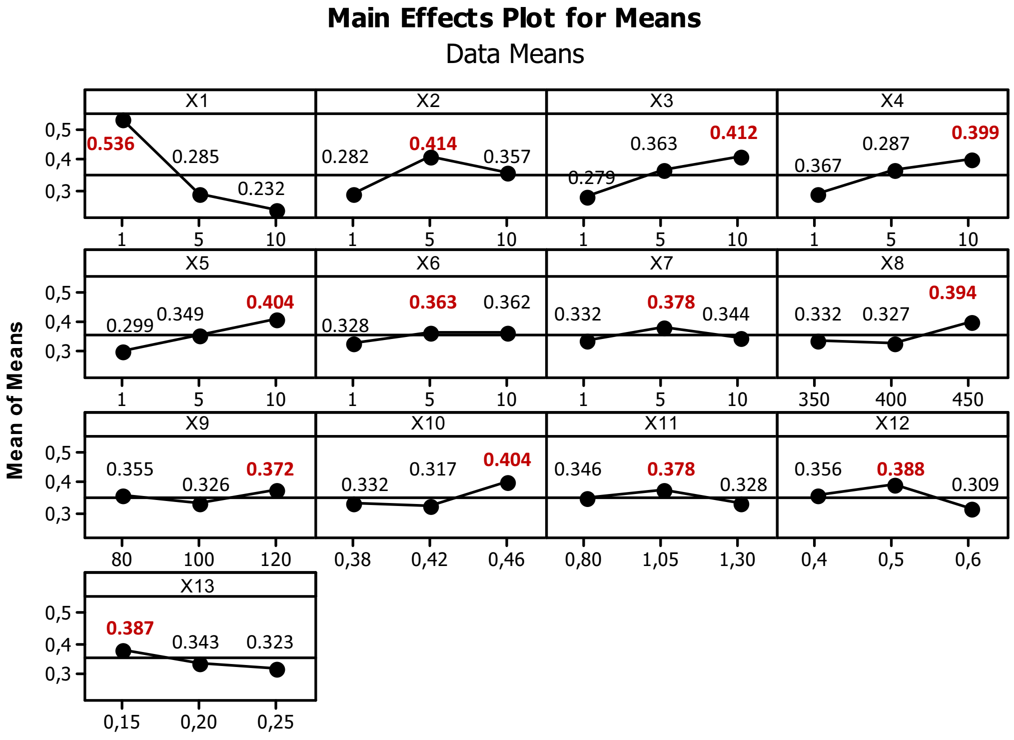

Fig. 3. Optimum factors' levels and means plots for factor effects.

Table 9
Improvement ratio between polymer concrete and reference concrete properties.

Responses	Definition	Reference concrete (M0)	[a]Optimal mixture levels after Taguchi experiments $(X_2)_1,(X_2)_2,(X_3)_3,(X_4)_3,(X_5)_3,(X_6)_2,(X_7)_2,(X_8)_3,(X_9)_3,(X_{10})_3,(X_{11})_2,(X_{12})_2,(X_{13})_1$	Anticipated improvement (dB)	Anticipated improvement (%)
1	Thermal conductivity (W/m K)	1.66	0.70	0.58	57.8[b]
2	Compressive strength (N/mm^2) 3rd day	44.40	29.39	−0.34	−33.8
3	Compressive strength (N/mm^2) 7th day	50.40	29.91	−0.41	−40.7
4	Compressive strength (N/mm^2) 28th day	60.90	36.4	−0.40	−40.2
5	Slump flow (cm)	16.0	14.0	−0.12	−12.5
6	Water absorption (%)	2.02	2.46	−0.22	−21.8
7	Splitting tensile strength (N/mm^2) 28 days	4.00	2.64	−0.34	−34.0
8	Production Cost ($/mm^2)	119.71	608.76	−4.08	−408
9	Water permeability (cm)	0.70	2.28	−2.26	−225.7

[a] Validation experiment results obtained by optimal mix level.
[b] $\left[\left(\frac{1.66-0.70}{1.66}\right) * 100\right] = 57.8$.

6.2. Morphology analysis of optimum PBC

The micro structural analysis of composites by SEM (Scanning Electron Microscopy) is useful tool to evaluate material compactness and homogeneity, degree of hydration and adhesion to materials [58]. As an example, cavernous in structure negatively affect the future compressive strength can be observed by SEM analysis [59]. The formation of a strong transition zone between polymer and cement paste shows that good adhesion between these materials that it is possible to analysis by SEM [60]. The C-S-H gel is the responsible for the mechanical properties of hydrated cement-based materials [61]. Therefore, the hydration product of the C-S-H gel take place predominantly in SEM images refers to will have high compressive strength. Moreover, the partial replacement of fine aggregate with polymer increases water absorption. This behavior is attributed to higher macro or capillar pores in PBC when compared to reference concretes. However, these pores higher scale than hydration products, so it could not see in SEM images.

SEM (Scanning Electron Microscopy) image of polymer blended concrete can be seen in Fig. 5. Crushed concrete samples taken from different points of the optimum PBC has been coated with carbon and SEM analysis has been performed. Transition zone between Calcium-Silica-Hydrate (C-S-H) gels provides strength to concrete and LDPE which is seen in Fig. 5a. Needle form and sheet like of C-S-H gel with Calcium Hydroxide (CH) structure of the hexagonal form which provides basic feature to concrete can be seen in Fig. 5b. In the other image, Dimethyl terephthalate (DMT) polymer is about 50 μm wide can be seen C-S-H gel and CH structure (Fig. 5c). Polypropylene with Calcium Hydroxide (CH) structure of the hexagonal form can also be seen in Fig. 5d.

Fig. 5e, f and h illustrate that C-S-H gel with Calcium Hydroxide (CH) structure of the hexagonal form and High Density Polyethylene (HDPE), C-S-H gel with fly ash and Polyethylene Naphthalate

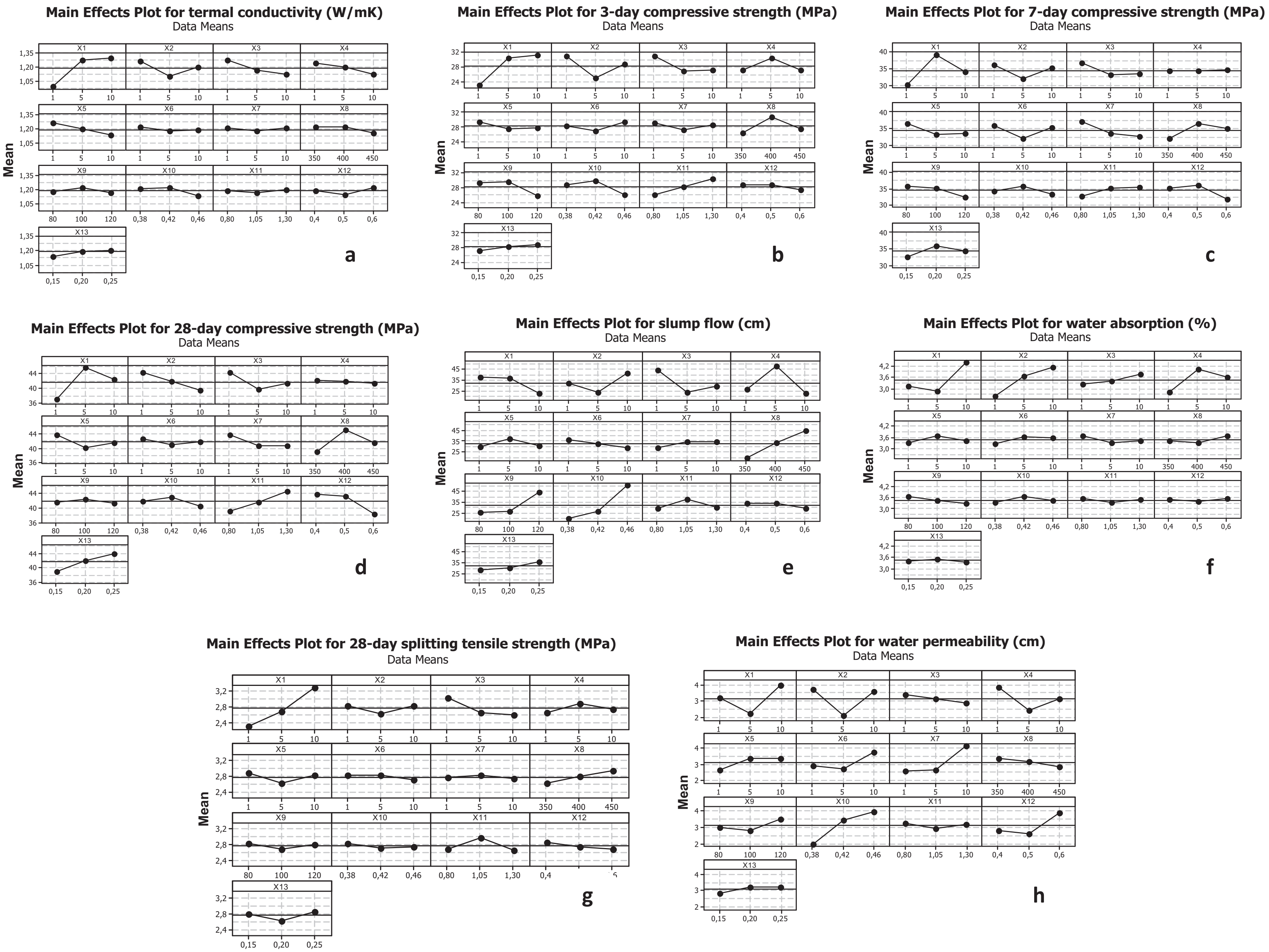

Fig. 4. Main effect plots for responses.

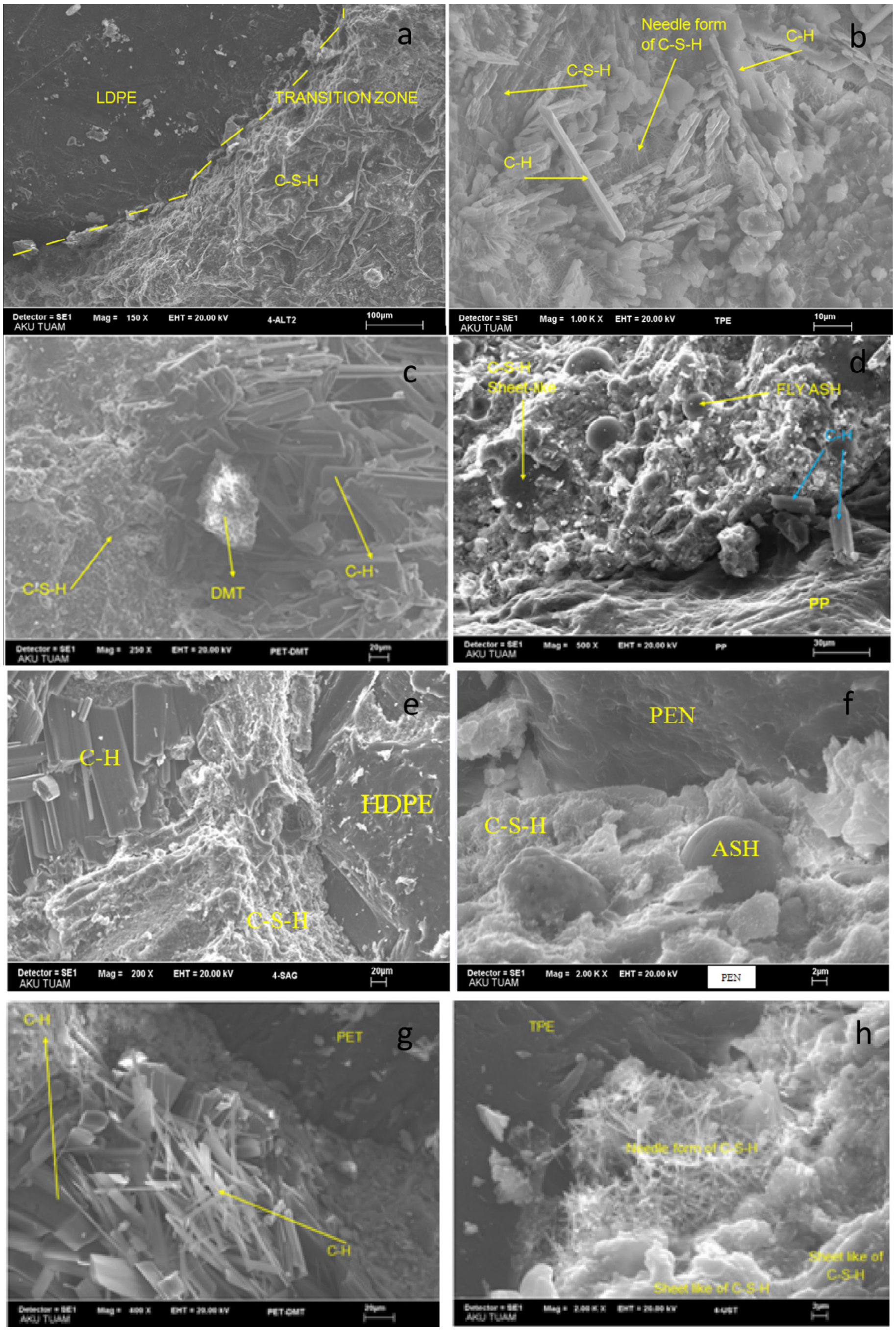

Fig. 5. SEM images of polymer mixed concrete.

(PEN) in PBC, needle form and sheet like of C-S-H gel with Thermoplastic Elastomer (TPE), respectively. Observation of the needle form and sheet like of C-S-H gel in PBC indicates that the mechanical properties of the PBC will increase with time (Fig. 5a–h). Analysis of transition zone between polymer and cement paste show that there is a strong bond polymer material and cement pastes. Benefiting from SEM analysis, it can be interpreted that there is a compact structure between polymer and concrete.

7. Conclusions

As the PBC consists of many conflicting factors; it is critical to use a systematic multi-response optimization methodology in order to determine the optimal mixes and to analyze the most effective factors under a set of constraints [9].

Reaching the desired level of heat insulation on an acceptable level of compressive strength has been tried to achieve with the multi-response optimization methods such as TOPSIS based Taguchi design. Polymer blended concrete having a lower thermal conductivity of 57.8% according to reference concrete has been achieved with a 28-day compressive strength loss of 40.2%. Polymer blended concrete which has been produced by optimal mixture ratios has a thermal conductivity of 0.70 W/m K and 28-day compressive strength of 36.8 MPa. Slump flow value of the optimum PBC is 14 cm. A descriptor example showed that the difference in the performance between the optimum PBC and the reference concrete is significant. The study provides evidence for the efficiency of the multi-response optimization methodology. The results showed that the proposed methodology is effective in determining the mixture proportions of PBC.

The most influential factors effect on PBC properties such as thermal conductivity, 3-day compressive strength, 7-day compressive strength, 28-day compressive strength, slump flow value, the percentage of water absorption, 28-day splitting tensile strength, production cost and water permeability have been found as polypropylene (X_3), thermoplastic elastomer (X_4) and dimethyl terephthalate (X_5) (Fig. 3). Polypropylene (X_3) and dimethyl terephthalate should be preferred in terms of production cost compared to thermoplastic elastomer. Furthermore, polypropylene (X_3) is more attractive option with regards to environmental problem. Thus, it can be performed on the one hand that eliminating the polymeric wastes that constitute an environmental problem and that are hard to disappear in the nature, as also ensuring energy saving.

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References

[1] F. Pacheco-Torgal, Y. Ding, S. Jalali, Properties and durability of concrete containing polymeric waste (tyre rubber and polyethylene terephthalate bottles): an overview, Constr. Build. Mater. 30 (2012) 714–724.

[2] P. Mounanga, W. Gbongbon, P. Poullain, P. Turcry, Proportioning and characterization of lightweight concrete mixtures made with rigid polyurethane foam wastes, Cem. Concr. Compos. 30 (2008) 806–814.

[3] B. Yeşilata, Y. Işıker, P. Turgut, Thermal insulation enhancement in concretes by adding waste PET and rubber pieces, Constr. Build. Mater. 23 (2009) 1878–1882.

[4] R. Demirboğa, A. Kan, Thermal conductivity and shrinkage properties of modified waste polystyrene aggregate concretes, Constr. Build. Mater. 35 (2012) 730–734.

[5] S. Akçaözoğlu, K. Akçaözoğlu, C.D. Atiş, Thermal conductivity, compressive strength and ultrasonic wave velocity of cementitious composite containing waste PET lightweight aggregate (WPLA), Compos. B 45 (2013) 721–726.

[6] B. Chen, N. Liu, A novel lightweight concrete-fabrication and its thermal and mechanical properties, Constr. Build. Mater. 44 (2013) 691–698.

[7] O. Youssf, M.A. ElGawady, J.E. Mills, X. Ma, An experimental investigation of crumb rubber concrete confined by fibre reinforced polymer tubes, Constr. Build. Mater. 53 (2014) 522–532.

[8] J. Lv, T. Zhou, Q. Du, H. Wu, Effects of rubber particles on mechanical properties of lightweight aggregate concrete, Constr. Build. Mater. 91 (2015) 145–149.

[9] B. Şimşek, Y.T. İç, E.H. Şimşek, A TOPSIS-based Taguchi optimization to determine optimal mixture proportions of the high strength self-compacting concrete, Chemom. Intell. Lab. Syst. 125 (2013) 18–32.

[10] L. Yang, H. Yan, J.C. Lam, Thermal comfort and building energy consumption implications – a review, Appl. Energy 115 (2014) 164–173.

[11] C.Y. Chang, R. Huang, P.C. Lee, T.L. Weng, Application of a weighted Grey-Taguchi method for optimizing recycled aggregate concrete mixtures, Cem. Concr. Compos. 33 (2011) 1038–1049.

[12] B. Şimşek, Y.T. İç, B. Şimşek, A.B. Güvenç, Development of a graphical user interface for determining the optimal mixture parameters of normal weight concretes: a response surface methodology based quadratic programming approach, Chemom. Intell. Lab. Syst. 136 (2014) 1–9.

[13] F. Bektaş, B. Aldemir, Analyzing mix parameters in ASR concrete using response surface methodology, Constr. Build. Mater. 66 (2014) 299–305.

[14] M.T. Cihan, A. Güner, N. Yüzer, Response surfaces for compressive strength of concrete, Constr. Build. Mater. 40 (2013) 763–774.

[15] Q. Li, L. Cai, Y. Fu, H. Wang, Y. Zou, Fracture properties and response surface methodology model of alkali-slag concrete under freeze–thaw cycles, Constr. Build. Mater. 93 (2015) 620–626.

[16] B. Akçay, M.A. Taşdemir, Optimisation of using lightweight aggregates in mitigating autogenous deformation of concrete, Constr. Build. Mater. 23 (2009) 353–363.

[17] J.J. Del Coz Diaz, P.J. Garcia-Nieto, F.P. Alvarez-Rabanal, M. Alonso-Martínez, J. Dominguez-Hernandez, J.M. Perez-Bella, The use of response surface methodology to improve the thermal transmittance of lightweight concrete hollow bricks by FEM, Constr. Build. Mater. 52 (2014) 331–344.

[18] N.U. Koçkal, T. Özturan, Optimization of properties of fly ash aggregates for high-strength lightweight concrete production, Mater. Des. 32 (2011) 3586–3593.

[19] L. Dvorkin, O. Dvorkin, V. Zhitkovsky, Y. Ribakov, A method for optimal design of steel fiber reinforced concrete composition, Mater. Des. 32 (2011) 3254–3262.

[20] M.A.A. Aldahdooh, N.M. Bunnori, M.A.M. Johari, Evaluation of ultra-high performance-fiber reinforced concrete binder content using the response surface method, Mater. Des. 52 (2013) 957–965.

[21] F. Köksal, Y. Şahin, O. Gencel, İ. Yiğit, Fracture energy-based optimisation of steel fibre reinforced concretes, Eng. Fract. Mech. 107 (2013) 29–37.

[22] B.S. Mohammed, O.C. Fang, K.M.A. Hossain, M. Lachemi, Mix proportioning of concrete containing paper mill residuals using response surface methodology, Constr. Build. Mater. 35 (2012) 63–68.

[23] E. Güneyisi, M. gesoğlu, Z. Algın, K. Mermerdaş, Optimization of concrete mixture with hybrid blends of metakaolin and fly ash using response surface method, Compos. B 60 (2014) 707–715.

[24] H. Narendra, K.U. Muthu, H. Al-Mattarneh, N.V.R. Naidu, B.S. Sowmya, Optimization of Self Compacting Concrete Mixes using Taguchi Method, vol. 17, ICCBT-A, Malaysia, 2008, pp. 191–204.

[25] E. Ozbay, A. Oztas, A. Baykasoglu, H. ve Ozbebek, Investigating mix proportions of high strength self compacting concrete by using Taguchi method, Constr. Build. Mater. 23 (2009) 694–702.

[26] H. Tanyıldızı, A. Coşkun, Performance of lightweight concrete with silica fume after high temperature, Constr. Build. Mater. 22 (2008) 2124–2129.

[27] İ. Türkmen, R. Gül, C. Çelik, A Taguchi approach for investigation of some physical properties of concrete produced from mineral admixtures, Build. Environ. 43 (2008) 1127–1137.

[28] M. Olivia, H. Nikraz, Properties of fly ash geopolymer concrete designed by Taguchi method, Mater. Des. 36 (2012) 191–198.

[29] A. Rahim, U.K. Sharma, K. Murugesan, A. Sharma, P. Arora, Multi-response optimization of post-fire residual compressive strength of high performance concrete, Constr. Build. Mater. 38 (2013) 265–273.

[30] A. Joshaghani, A.A. Ramezanianpour, A. Golroo, Optimizing pervious concrete pavement mixture design by using the Taguchi method, Constr. Build. Mater. 101 (2015) 317–325.

[31] R. Mohebi, K. Behfarnia, M. Shojaei, Abrasion resistance of alkali-activated slag concrete designed by Taguchi method Abrasion resistance of alkali-activated slag concrete designed by Taguchi method, Constr. Build. Mater. 98 (2015) 792–798.

[32] H. Tanyıldızı, M. Şahin, Application of Taguchi method for optimization of concrete strengthened with polymer after high temperature, Constr. Build. Mater. 79 (2015) 97–103.

[33] C. Panagiotopoulou, S. Tsivilis, G. Kakali, Application of the Taguchi approach for the composition optimization of alkali activated fly ash binders, Constr. Build. Mater. 91 (2015) 17–22.

[34] O. Keleştemur, E. Arıcı, S. Yıldız, B. Gökçeri, Performance evaluation of cement mortars containing marble dust and glass fiber exposed to high temperature by using Taguchi method, Constr. Build. Mater. 60 (2014) 17–24.

[35] K. Onoue, H. Tamai, H. Suseno, Shock-absorbing capability of lightweight concrete utilizing volcanic pumice aggregate, Constr. Build. Mater. 83 (2015) 261–274.

[36] A.N.S. Alqadi, K.N.B. Mustapha, Development of self-compacting concrete using contrast constant factorial design, J. King Saud Univ. Eng. Sci. 2 (2013) 105–112.

[37] P.S. Lovato, E. Possan, D.C.C. Molin, A.B. Masuero, J.L.D. Ribeiro, Modeling of mechanical properties and durability of recycled aggregate concretes, Constr. Build. Mater. 26 (2012) 437–447.

[38] R. Yu, P. Spiesz, H.J.H. Brouwers, Mix design and properties assessment of ultra high performance fibre reinforced concrete, Cem. Concr. Res. 56 (2014) 29–39.

[39] T.-L. Su, H.-W. Chen, C.-F. Lu, Systematic optimization for the evaluation of the microinjection molding parameters of light guide plate with TOPSIS-based Taguchi Method, Adv. Polym. Technol. 29 (1) (2010) 54–63.

[40] G.-B. Hong, T.-L. Su, Statistical analysis of experimental parameters in characterization of ultraviolet-resistant polyester fiber using a TOPSIS-Taguchi method, Iran. Polym. J. 21 (12) (2012) 877–885.

[41] T.-S. Lan, Taguchi optimization of multi objective CNC machining using TOPSIS, Inf. Technol. J. 8 (6) (2009) 917–922.

[42] J.-C. Lu, T. Yang, C.-T. Su, Analysing optimum push/pull junction point location using multiple criteria decision-making for multistage stochastic production system, Int. J. Prod. Res. 50 (19) (2012) 5523–5537.

[43] C.L. Hwang, K.P. Yoon, Multiple Attributes Decision Making: Methods and Applications, Springer-Verlag, New York, 1981.

[44] M. Yurdakul, Y.T. Ic, Analysis of the benefit generated by using fuzzy numbers in a TOPSIS model developed for machine tool selection problems, J. Mater. Process. Technol. 209 (2009) 310–317.

[45] Y.T. İç, An experimental design approach using TOPSIS method for the selection of computer-integrated manufacturing technologies, Rob. Comput. Integr. Manuf. 28 (2012) 245–256.

[46] ASTM C 1113-90/C1113M, Test Method for Thermal Conductivity of Refractories by Hot Wire, 2013.

[47] EN 12390/3, Testing Hardened Concrete—Part 3, Compressive Strength of Test Specimens, Turkish Standardization Institute, Ankara, 2010 (in Turkish).

[48] EN 12390-6, Testing Hardened Concrete—Part 6, Determination of Splitting Tensile Strength of Concrete Specimens, Turkish Standardization Institute, Ankara, 2002 (in Turkish).

[49] B. Şimşek, Y.T. İç, E.H. Şimşek, A RSM-based multi-response optimization application for determining optimal mix proportions of standard ready-mixed concrete, Arab. J. Sci. Eng. (2015) 1–9, http://dx.doi.org/10.1007/s13369-015-1987-0.

[50] EN 12350/2, Testing Fresh Concrete-Part 5, Flow Table Test, Turkish Standardization Institute, Ankara, 2010, pp. 1–10 (in Turkish).

[51] EN 12390-7, Testing Hardened Concrete—Part 7, Density of Hardened Concrete, Turkish Standardization Institute, Ankara, 2010 (in Turkish).

[52] TS EN 12390/8, Testing Hardened Concrete-PART 8, Depth of Penetration of Water Under Pressure, Turkish Standardization Institute, Ankara, 2002 (in Turkish).

[53] T. Yang, P. Chou, Solving a multi-response simulation-optimization problem with discrete variables using a multiple-attribute decision-making method, Math. Comput. Simulat. 68 (1) (2005) 9–21.

[54] S.M. Abdelkader, E.R. Pozo, A.M. Terrades, Evolution of microstructure and mechanical behavior of concretes utilized in marine environments, Mater. Des. 31 (7) (2010) 3412–3418.

[55] T. Uygunoğlu, A. Keçebaş, LCC analysis for energy-saving in residential buildings with different types of construction masonry blocks, Energy Build. 43 (2011) 2077–2085.

[56] Y. Kuo, T. Yang, G.W. Huang, The use of a grey-based Taguchi method for optimizing multi-response simulation problems, Eng. Optim. 40 (6) (2008) 517–528.

[57] R.D. Koyee, S. Schmauder, U. Heisel, Eisseler, Numerical modeling and optimization of machining duplex stainless steels, Prod. Manuf. Res. 3 (1) (2015) 6–83, http://dx.doi.org/10.1080/21693277.2014.990539.

[58] O.Y. Marzouk, R. Dheilly, M. Queneudec, Valorization of post-consumer waste plastic in cementitious concrete composites, Waste Manage. 27 (2007) 310–318.

[59] L. Gu, T. Özbakkaloğlu, Use of recycled plastics in concrete: a critical review, Waste Manage. 51 (2016) 19–42.

[60] A.B. Fraj, M. Kismi, P. Mounanga, Valorization of coarse rigid polyurethane foam waste in lightweight aggregate concrete, Constr. Build. Mater. 24 (2010) 1069–1077.

[61] S. Goni, M. Frias, I. Vegas, R. Garcia, R.V. De la Villa, Quantitative correlations among textural characteristics of C-S-H gel and mechanical properties: case of ternary Portland cements containing activated paper sludge and fly ash, Cem. Concr. Compos. 34 (2012) 911–916.