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Application of Taguchi method for the design of cement mortars containing waste materials

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Abstract: Industries related to the acquiring of building materials may soon face a shortage of natural resources and an associated increase in costs of their acquisition. Therefore, it is necessary to look for possible ways to reduce the exploitation of natural resources and instead use recycled raw materials. Such policies fit into one of the most important trends in modern construction, which is sustainable development. In the conducted research, the Taguchi method was utilized in order to investigate the impact of modifying cement mortars with rubber and cork waste on the selected properties of the obtained composites. Thanks to the above method, we managed to obtain the desired information about mortars in a shorter time and at a lower cost than using traditional testing methods. Using the selection in planning method, we confirmed that rubber waste can be a good substitute for sand in mortars.

Keywords: rubber waste, cork waste, cement mortars, design of experiments, Taguchi method

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Introduction

Modern science and industry use advanced recycling technologies to care for the environment. Global challenges such as overfilled landfill sites, climate change, and at the same time lack of natural resources require effective action, no more so than from the construction sector. One solution to the above-mentioned problems can be obtained by undertaking research into the development of alternative processes for producing construction materials using properly prepared post-production waste before it is disposed of in landfills (Verian et al., 2018). Recently, this topic has appeared in many a scientific article, in which the authors have attempted to evaluate the effectiveness of using waste materials in one of the most popular building composites, concrete. The popularity of this material increases the demand for raw materials, such as aggregate, which is necessary for its production. this approach results in the depletion of natural aggregate resources in many countries. At the same time, a huge amount of concrete waste is created. Therefore, research has been conducted into the possibility of using concrete waste for the production of new components (Deng et al., 2019; Rughooputh et al., 2017). Evangelista and de Brito (2017) conducted strength tests of concretes containing small fractions of aggregates produced from recycled construction and demolition waste. They found that the use of recycled aggregates in structural components does not significantly affect bending strength, even if the load capacity is slightly lower than that of conventional concretes. Ngohpok et al. (2018) and Wongkvanklom et al. (2018) showed that the use of recycled aggregates produced composites of similar strength properties, while at the same time being characterized by better thermal and acoustic insulation. Selected properties of concrete and mortars were tested, in which traditional components, most often aggregates or cement, were replaced with waste products such as plastic, glass, cork, rubber (Liu et al., 2019; Ling et al., 2013), and recycled ceramic aggregate (Zegardło et al., 2018; Alves et al., 2014). The incorporation of waste materials into the mix changes the mechanical and physical properties and durability of the composites. Analysis of the available literature leads us to conclude that we have managed to obtain satisfactory properties in concrete and resin mortars using plastic waste such as polyurethane, polyurethane foam (Fraj et al., 2010; Mahdi at al., 2010), expanded polystyrene and polystyrene (Herki, 2017; Laukaitis et al., 2005), polyamide and polypropylene (Kim et al., 2010; Schmidt & Cieślak, 2008), low and high-density polyethylene and poly (vinyl chloride) (Galvão et al., 2011; Kou et al. 2009), bamboo fibers from construction waste (Akinyemi & Omoniyi, 2018), polyethylene terephthalate (Dębska, 2015; Dębska & Lichołai, 2017), and polyisocyanurate foam (Kanchanapiya et al., 2018).

Ecological, as well as technical reasons, also encourage the use of cork waste as a substitute for aggregates during the production of building materials, including concretes and mortars. Cork granules are made from waste obtained during trimming operations, hence the cost of such granules is much lower compared to the price of first quality cork. Around the world, industrially produced cork generates up to 20-30% waste in the form of granules (these are 0-2 mm fractions) on average around 50,000 tonnes/year (Matos et al., 2015). The popularity of cork stems from the fact that it is flame-retardant (carbonizes and does not burn with a flame), and has antimicrobial and antifungal properties. It does not absorb odors and is an excellent barrier for liquids and gases. The density of cork is in the range of 120-240 kg/m^3 (for comparison, sand density is 1650 kg/m^3) which puts it in the role of a light filling material. Thanks to its structure, in which 80-90% of the filling is air, it is an excellent thermal and acoustic insulator. Panesar and Shindman (2012) used cork waste of various grain size as a substitute for aggregates in mortars and cementitious concrete in the amount of 0-20%. Brás et al. (2013, 2014) obtained cement composites in which the cork replaced the aggregate in an amount of up to 80% by mass. The tests of these assemblies have shown that the material resulting from the modification, especially when using a lime binder, can be an effective solution for the correction of thermal bridges in a building. It is also possible to obtain satisfactory strength parameters using cork dust in self-compacting concrete (Matos et al., 2015). In addition, the improvement of cork mortar parameters can be achieved using the hydrophobization process (Barnat-Hunek et al., 2017). Replacing the aggregate with cork in epoxy mortars decreases the strength parameters, but also allows for a significant reduction of the weight which, in the case of a large number of prefabricated elements made of this material, is very important (Nóvoa et al., 2004).

Many scientists also devote considerable attention to rubber waste. Due to the constantly increasing production of car tires, there is a need to recycle used tires. Reprocessing of rubber requires a lot of time-consuming, labor-intensive and costly operations. The recycled material is usually characterized by poorer physical and mechanical properties and is not competitive with the original rubber materials. An interesting solution seems to be the use of this waste for the production of concretes and mortars. Some authors have reviewed articles regarding the possibility of using rubber waste in cementitious concrete (Thomas & Gupta, 2016). Research has shown that there is a promising future in the utilization of used rubber tires as a partial substitute for aggregates in cement concrete. The literature explains that it is possible to make concrete mixes with the addition of shredded tire waste and concrete used for special applications, obtained from lightweight rubber aggregate. Concrete modified with rubber waste shows high resistance to freezing-thawing, acid attack, and chloride ion penetration. The same authors also published a series of articles (Thomas & Gupta, 2015; Thomas et al., 2016; Thomas et al. 2015) wherein they described their own research on concrete, in which 0-20% of the aggregate was replaced with rubber waste. For the composites obtained in this way, they determined a number of properties, including strength parameters, adhesion, water absorption, sulphate attack, depth of carbonation, and chloride penetration depth. The authors assumed a discretization step of 2.5% of rubber waste and a water-cement ratio of 0.4; 0.45 and 0.5. All these factors contributed to the fact that they had to make a huge number of research samples (over 800). Thomas and Gupta, summarizing the results, said that they were promising. The addition of rubber waste does diminish the concrete strength parameters, but with a content of up to 7.5% modifier, the strength drop was relatively small. A similar situation occurs with the sulphate attack. However, even in the presence of about 12% of the waste material, a lower water absorption and degree (intensity) of carbonation was obtained than it is possible to achieve for reference concretes. Issa and Salem (2013) made concrete samples with 100% substitution of aggregates. According to these authors, the allowable compressive strength values can be obtained at 25% of the waste content. Gupta et al. (2014) conducted similar tests adding to the concrete mix up to 20% waste rubber ash and rubber fibers. Youssf et al. (2016) attempted to improve the strength properties of concretes modified with rubber waste by, among other methods, pre-treatment of waste with sodium hydroxide solution, using silica fume additives and increasing the cement content. Based on the research, the authors gave the recommended composition of the concrete mix, however, it seems that without the use of the theory of experiment planning, the picture may be incomplete.

Nowadays, all profitable technical innovations develop largely on the basis of scientific research. In turn, scientific research is a combination of theory and experiment, with experiments generating disproportionately high costs compared to theoretical works (Dębska & Lichołai, 2016; Dębska et al., 2018; Lichołai et al., 2019; Musiał, 2018). In order to obtain the necessary experimental scientific data as quickly and as cheaply as possible, the theory of the experiment should be used e.g. Taguchi method. That plan is included in the Experiment Planning module, which is part of the STATISTICA program.

Taguchi method has been used to prepare and carry out the research described in this article. The research concerned cement mortars in which 0-50% vol. aggregates were replaced with cork waste or rubber waste. Application of the theory of the experiment allowed for a significant reduction in the number of research samples, and also reduced the cost and time necessary to carry out laboratory tests. At the same time, it enabled the fullest information on the factors affecting the production of new mortars modified with two types of waste.

1. Materials and methods

1.1. Design of the experiment

The strength properties of concrete mixes depend on various factors related to the type, quality, proportions of ingredients, production methods, method of care, and load conditions. This paper attempts to investigate the possibilities of using the experimental design technique – Taguchi method – to indicate the factors that have the greatest impact on changes in selected properties of cement mortars containing two types of waste: cork (K) and rubber (G).

The Taguchi method is an effective tool for designing experiments. Thanks to its application, it is possible to significantly reduce the number of laboratory tests required, while maintaining the level of influence of each variable on the final result. The aim of the Taguchi method may be to determine the value of parameters (e.g. mortar composition) that will ensure obtaining the material with the best quality according to the defined criterion. The impact of design parameters (input variables) on the final result depends on the loss function, which measures the deviation between the experimental value and the desired value. In the Taguchi approach, the loss function is further transformed into a signal-to-noise ratio (SNR), which is a logical function of the expected results (Ferdous et al., 2017; Kowalczyk, 2014). Based on well-known regularities considered during the analysis of processes related to determining the strength of cement mortars, the following parameters are chosen as the basic factors influencing the strength characteristics of composites modified with waste:

a) the water-cement ratio (W/B), and thus the binder content in the mortar (B);
b) percentage change of waste aggregates (R);

c) type of waste used (AT);
d) curing time (T).

The selected types of input parameters for planned experiments and assumed levels of changes in their values are presented in Table 1.

Table 1. Selected design parameters and their levels (*own research*)

	Factors			
	A-Aggregate type	B-Aggregate content [%]	C-Cement content [%]	D-Curing time [day]
Level 1	K	0	50	7
Level 2	G	50	57	28

Using the STATISTICA program and the module available in it *Planning the experiments/Experiments according to the Taguchi method (orthogonal tables)* an orthogonal array was generated L16. The Table generated by the STATISTICA program, including 4 input quantities and two output quantities, is shown in Table 2.

Table 2. Combinations of the experiments in Taguchi's method (*own research*)

St. Run	Design summary L16: 15 factors; all factors have 2 levels (Factors are denoted by numbers)																
	A 1	B [%] 2	Unused 3	C [%] 4	Unused 5-7			D [day] 8	Unused 9-15							F_f [MPa]	F_c [MPa]
1	K	K0	1	C57	1	1	2	1	2	1	2	1	2	2	1	6.68	33.99
2	K	K0	1	C57	1	1	2	2	1	2	1	2	1	1	2	7.61	37.37
3	K	K0	1	C50	2	2	1	1	2	1	2	2	1	1	2	6.35	28.7
4	K	K0	1	C50	2	2	1	2	1	2	1	1	2	2	1	8.84	35.15
5	K	K50	2	C57	1	2	1	2	1	2	1	1	2	1	2	3.79	10.09
6	K	K50	2	C57	1	2	1	1	2	1	2	2	1	2	1	4.23	4.94
7	K	K50	2	C50	2	1	2	2	1	2	1	2	1	2	1	4.05	9.00
8	K	K50	2	C50	2	1	2	1	2	1	2	1	2	1	2	5.08	9.25
9	G	K0	2	C57	2	1	1	1	1	1	1	1	1	2	2	6.97	29.18
10	G	K0	2	C57	2	1	1	2	2	2	2	2	2	1	1	8.10	22.46
11	G	K0	2	C50	1	2	2	1	1	1	1	2	2	1	1	6.72	33.78
12	G	K0	2	C50	1	2	2	2	2	2	2	1	1	2	2	8.53	34.45
13	G	K50	1	C57	2	2	2	2	2	2	2	1	1	1	1	4.61	14.04
14	G	K50	1	C57	2	2	2	1	1	1	1	2	2	2	2	5.17	15.10
15	G	K50	1	C50	1	1	1	2	2	2	2	2	2	2	2	3.80	8.83
16	G	K50	1	C50	1	1	1	1	1	1	1	1	1	1	1	4.27	11.88

1.2. Materials

In order to make mortar samples, Class 32,5 R cement from the Polish company Ożarów was used, which, according to the manufacturer's declaration, meets the requirements for the composition and criteria of conformity of common use cements. The mixing water came from the water supply network. Quartz sand with a bulk density of 1.65 g/cm^3 was used as the aggregate. From the manufacturer of cork products, waste was obtained in the form of granules (Fig. 1a) with a grain size: 0.2-2.0 mm and bulk density at the level of 0.07 g/cm^3. In the second series of mortars made, quartz sand was partially replaced by waste rubber granules obtained from car tires (Fig. 1b) with a grain size: 0-2.0 mm and bulk density at the level of 1.65 g/cm^3. Each of the added waste materials was a substitute for aggregates in the amount of 0-50% by volume. Sand replacement was performed fraction to fraction based on the grain curves of the aggregates used, as shown in Figure 2.

a) b)

Fig. 1. Waste granulate used to make mortar samples: a) cork, b) rubber (*own research*)

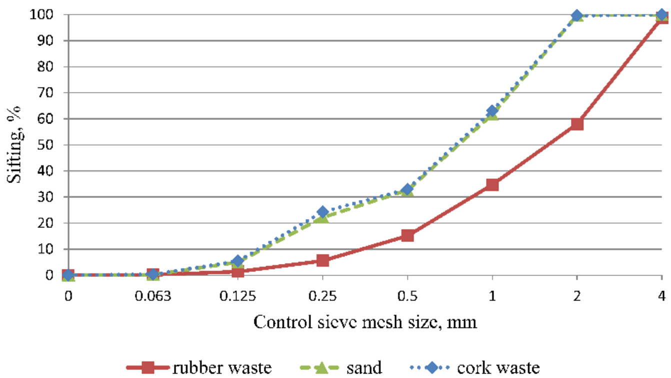

Fig. 2. Grain-size curves for waste materials and sand used for testing (*own research*)

1.3. Preparation and testing of samples

Based on the experimental plan developed (Table 1), 40x40x160 mm samples were made, 3 specimens for each series. Each batch consisted of a constant amount of 450 g of cement and the required amount of water added in accordance with the calculated value of the W/B ratio. The basic squeeze content assigned for the reference series is 1350 g. Cement was poured into a bowl with water and placed in the machine. It was also necessary to supplement the aggregate feeder with pre-weighed sand and waste. The programmed mixer adjusted the rotation, aggregate dosage and mixing time accordingly. The mortars prepared in this way were placed in dismountable steel molds, which were thoroughly cleaned and lubricated beforehand. The mortar was laid in two layers, which were thickened with 60 strokes of the shaker. After compacting, the top layer was levelled and the surfaces were protected against excessive drying with a glass plate. The molds were stored for 24 hours in a laboratory cabinet in conditions with the required constant temperature and humidity. After 24 hours the specimens were removed from the mold, signed and placed in a water bath, where they were seasoned for 7 and 28 days, respectively. Strength tests were carried out in machines adapted for this purpose, equipped with appropriate inserts for bending and compression.

2. Discussion

Due to the fact that in the plan developed for the Taguchi method, the output variables constituted bending and compression strength, so the features for which the maximum was sought, the analysis began with choosing the type of issue identified as: the bigger the better, available among the alternatives listed in the drop-down list: Type of problem. In the Analysis of experience by the Taguchi method, a result window named Intermediate Limits is shown, the content of which is shown in Table 3.

Table 3. Overview of marginal means (*own research*)

Effect	Average Eta by Factor Levels Mean = 17.5296 Sigma = 2.94342				
	Level	Means	Paramet. Estimate	St. Dev.	St. Error
Aggregate type	K	17.22922	–0.30042	3.253991	0.379220
	G	17.83007	0.30042	2.787542	0.350989
Aggregate content [%]	K0	20.17212	2.64247	1.022612	0.212588
	K50	14.88718	–2.64247	1.248624	0.234908
Cement content [%]	C57	17.48532	–0.04432	2.951832	0.361184
	C50	17.57397	0.04432	3.138047	0.372402
Time [day]	T7	16.91234	–0.61731	2.634720	0.341232
	T28	18.14695	0.61731	3.279082	0.380679

Table 3 presented the average (for the Eta = S/N coefficient) for each value of each factor. The program also calculated the parameter estimators, i.e. the deviations of the mean values of individual input values from the general average. All above averages can be presented on a collective chart (Fig. 3). Figure 3 is a visual summary of the experiments. It presents a graph of the average values of Eta (S/N ratio) on the value of factors.

Interpreting the data shown in Figure 3, you can easily recognize the best settings for each input quantity, i.e. settings that maximize the value of Eta = S/N. In Figure 3, dashed lines indicate the double standard deviation range around the average quality loss function (Eta). The standard deviation was calculated based on the error component in the last row of Table 4. It contains the results of the analysis of variance, which assesses the degree of influence of particular input values on the obtained results.

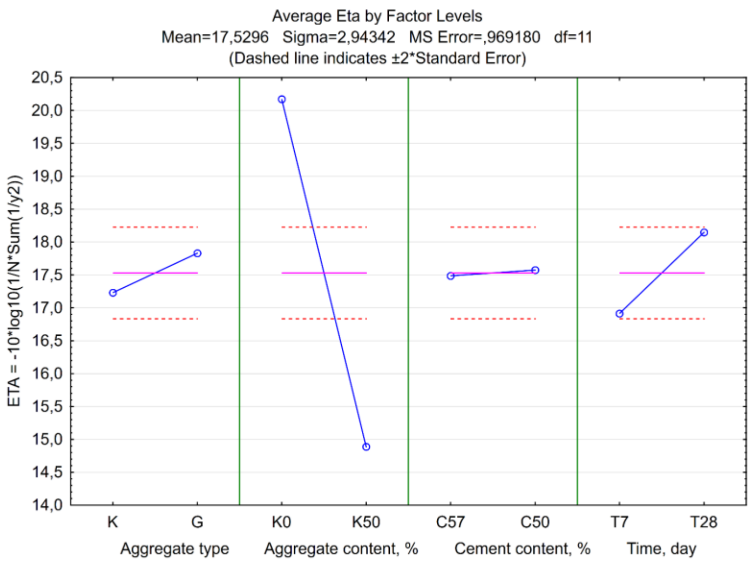

Fig. 3. Overview of marginal means (*own research*)

Table 4. The results of the analysis of variance (*own research*)

Effect	Analysis of Variance Mean = 17.5296 Sigma = 2.94342				
	SS	df	MS	F	p
1-Aggregate type	1.4441	1	1.4441	1.4900	0.247741
2-Aggregate content [%]	111.7224	1	111.7224	115.2752	0.000000
3-Cement content [%]	0.0314	1	0.0314	0.0324	0.860354
4-Time [day]	6.0971	1	6.0971	6.2910	0.029080
Residual	10.6610	11	0.9692		

From the initial analysis of variance it can be concluded that the Aggregate Content, and to a slightly smaller extent Time, has the dominant influence on the obtained results. In the last column of Table 4 for these input quantities, the value of p is 0.000 and 0.029, respectively. The low value (relative to the significance level of $\alpha = 0.05$) of test probabilities p for these two input data gives a high probability of determining the significance of the influence of these parameters on the value of the objective function.

The STATISTICA program enables the Eta button to be activated in optimal conditions, and thus the card shown in Table 5 is generated.

All values assume here optimum values, i.e. those that give the highest value of the S/N ratio. Considering the earlier conclusions that Aggregate content and Time have a significant influence, it can be concluded that an average value of Eta equal to 17.5296 can be obtained for mortars modified with rubber waste and maturing for 28 days.

Table 5. Expected values of the quality loss function (Eta) in optimal conditions (*own research*)

Factor	Expected S/N Ratio under Optimum Conditions Mean = 17.5296 Sigma = 2.94342		
	Level	Effect Size	Standard Error
1-Aggregate type	G	0.30042	0.348063
2-Aggregate content [%]	K0	2.64247	0.348063
3-Cement content [%]	C50	0.04432	0.348063
4-Time [day]	T28	0.61731	0.348063
Expected S/N		21.13417	

Conclusions

The conducted research used Taguchi method of experiment planning. This approach allowed the assessment of the impact of composite composition modifications on selected mortar properties. An analysis of the obtained results drew the following conclusions:

- using the method of planning the experiment allows us to indicate the input quantities that significantly affect the process of obtaining mortars,
- confirmation of the assumed substantive hypotheses is obtained in a shorter time and at lower costs than using traditional methods while conducting research.

Summing up the results obtained as a result of planning the experiment by the Taguchi method it was found that the Aggregate content and Time input quantities have the greatest impact on the strength parameters of cement mortars. Giving both factors the values determined by the program, i.e. (1) an indication of the need to use rubber waste as a composite modifier and (2) adopting a maturation time of 28 days, allows us to achieve optimal results, i.e. produces mortars that have the highest values of flexural and compression strength.

The possibility of using waste materials in mortars is a valuable contribution to sustainable development in construction. The analyses carried out state clearly that among the two modifiers used, rubber waste is a more valuable substitute for sand in mortars, because mortars obtained after their application have better properties. This is important information, as this waste is much more common and harmful to the environment than cork waste.

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